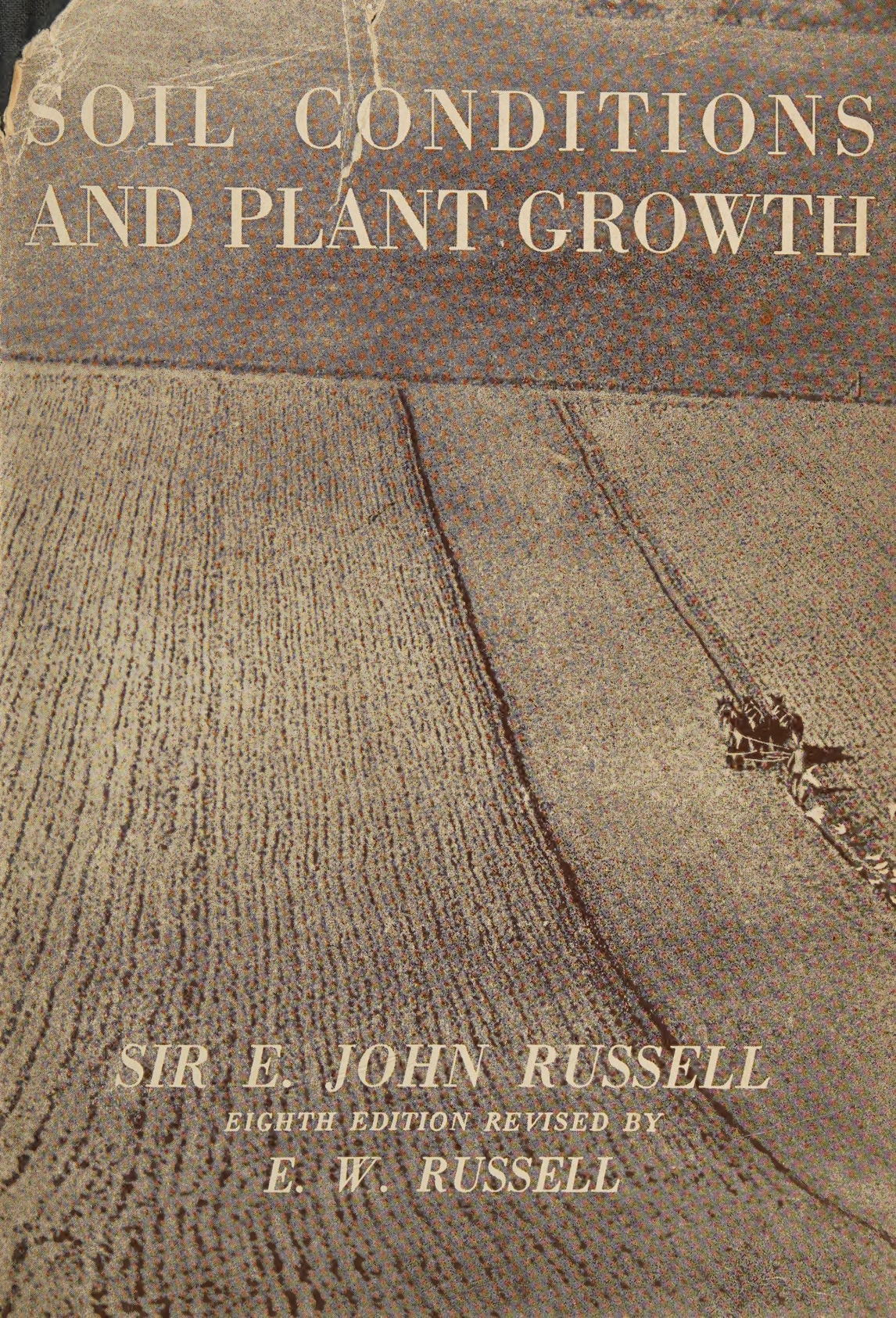
SOIL CONDITIONS AND PLANT GROWTH



SIR E. JOHN RUSSELL

EIGHTH EDITION REVISED BY

E. W. RUSSELL

Some Press Opinions

Probably the most widely known, and certainly the most widely quoted, book on soils.

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[*Continued on back flap*

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THIRD IMPRESSION

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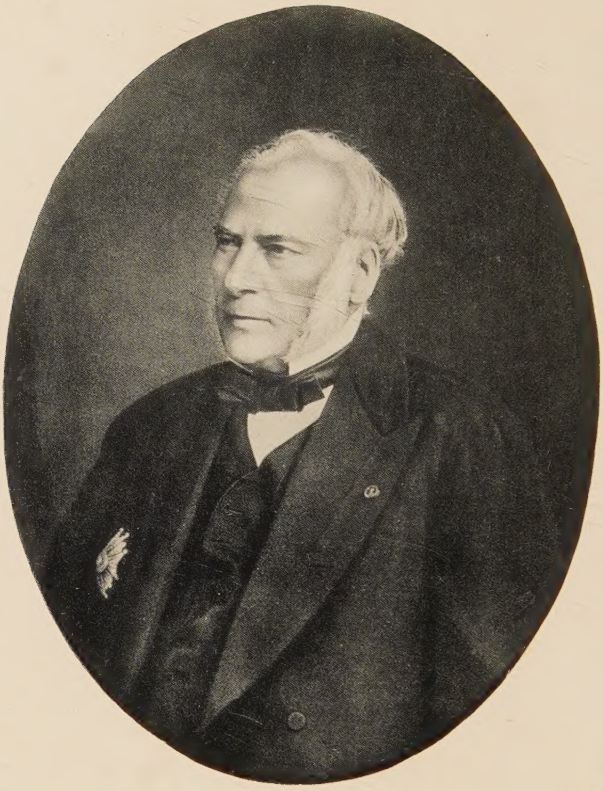

JEAN BAPTISTE DIEUDONNE BOUSSINGAULT
1802–1887

The Founder of Modern Agricultural Chemistry

SOIL CONDITIONS & PLANT GROWTH

BY

SIR E. JOHN RUSSELL

D.Sc., F.R.S.

FORMERLY DIRECTOR OF THE ROTHAMSTED EXPERIMENTAL STATION AND OF THE IMPERIAL BUREAU OF SOIL SCIENCE HARPENDEN
PRESIDENT OF THE BRITISH ASSOCIATION, 1949

EIGHTH EDITION

RECAST AND REWRITTEN BY

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READER IN SOIL SCIENCE IN THE UNIVERSITY OF OXFORD

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PREFACE TO THE EIGHTH EDITION

WHEN SIR JOHN RUSSELL was about to retire from the Directorship of Rothamsted Experimental Station in 1943, he asked me to take over full responsibility for the future editions of this book, and he gave me authority to make whatever alterations I considered desirable to help it fulfil its original function of presenting an up-to-date account of our knowledge of the soil as a medium for plant growth. I have made full use of this liberty, and have rewritten and recast the whole text with the exception of Chapter 1, which has hardly been altered since the First Edition, and of some other minor passages. I have also increased the number of Chapters and altered the arrangements of the material in the book very considerably. I have, however, tried to keep within the general framework that Sir John Russell gave the book when it was first published in 1912 and which he has maintained ever since.

I have also taken this opportunity to make an alteration in the terminology used in the text. I have purposely used the words calcium, magnesium, potassium and sodium instead of lime, magnesia, potash and soda, and in consequence I have expressed all chemical analyses involving these elements in terms of the simple cations and not of the oxide. I have further used the same convention for all the other elements, and in particular the phosphorus content of plants, fertilisers and soils have been given in terms of their phosphorus contents, and not in terms of phosphorus pentoxide. There is no justification for using P_2O_5, except for historical and legal reasons, and though it might be more logical to express compositions in terms of the H_2PO_4 ion, for the time being I prefer using the element. The only place in which I have retained the old convention is in the chapters dealing with the weathering of rocks and the formation of soils, since this convention is still universally followed by mineralogists. I hope, however, that even this convention can soon be dropped so that, in particular, clays can be described by their silicon-aluminium rather than by their silica-alumina ratio.

One of the functions of this book has been to give a critical account of our knowledge in each subject, and for this reason references have always been quoted, wherever possible, for all the statements made. This has always been one of the essential features of the book in the past, and I consider that it should remain so in the future. But the revision has taken me much longer than I expected, and though I

have always tried to give references to the statements made, I have often been obliged to give references to work that was familiar to me, without full search of the literature for establishing priority. Hence I hope that any worker whose work I have overlooked, but ought to have quoted, will forgive my omission and inform me, so that I can correct the omission in a future edition.

I could not have prepared this revision without receiving very considerable help from a large number of research workers throughout the world. Further, most of the work of revision of this book was done whilst I was a member of the Rothamsted staff, and it is with particular pleasure that I can take this opportunity of thanking both the present Director, Sir William Ogg, for allowing me whatever facilities I needed at Rothamsted for the purpose, and also the very many past and present members of the staff of both Rothamsted and the Commonwealth Bureau of Soil Science for their unfailing help whenever requested. I cannot possibly make adequate acknowledgement here to all those who have given me help, though I want to make personal acknowledgements to the following for the great help they have given me: Miss L. M. Crump, Drs. W. E. Brenchley, J. Meiklejohn, K. Warington, H. G. Thornton, H. L. Penman and R. K. Schofield, and Mr. J. W. Weil at Rothamsted, Dr. A. G. Norman at Camp Detrick, Maryland, and Dr. R. Scott Russell at Oxford. I am also greatly indebted to my wife for undertaking most of the work of preparing the indexes.

Finally it is a pleasant and proper filial duty to thank the original author for giving me so many opportunities to acquire the knowledge necessary for taking over the revision of this book from him.

E. W. Russell

Department of Agriculture,
University of Oxford.

February, 1950

PREFACE TO THE FIRST EDITION

I HAVE ENDEAVOURED in the following pages to give a concise account of our present knowledge of the soil as a medium for plant life. At first sight the subject appears very simple; in reality it is highly complex and trenches on several different subjects with which no one individual can claim to have any adequate knowledge, and, what is perhaps a greater disadvantage, it has grown up very unsystematically. Chemists, botanists, bacteriologists, geologists, and agriculturalists have all contributed something, but usually in connection with their own special problems and not with the idea of developing a new subject. It has usually been reckoned part of the somewhat vague mixture known as agricultural chemistry, and has often been considered more suitable for farmers' lectures than for pursuit for its own sake.

As a result of its history the subject is now in a rather confused state. Suggestions thrown out by men eminent in some other branch of science have been accepted without much serious examination; illustrations used in farmers' lectures to drive home some important point to an audience before whom lucidity is above all things necessary, have acquired the force of established facts; whilst statements, and sometimes even substances, have come to be believed in for no better reason than that people have talked a great deal about them.

In recent years, however, its recognition as a basis of national wealth has given the soil a high degree of technical importance, whilst the remarkable constitution it appears to possess, the variety of its microscopic inhabitants and their close connection with plant life, all impart to its study unusual scientific interest. The time, therefore, seems ripe for a critical examination of the foundations for our beliefs, and this task is rendered easier by the advances made of late years on the Continent, in America and in this country. As the foreign literature is not generally available for English readers I have given the evidence in some detail, so that my fellow agricultural chemists may see it for themselves, and the student of pure science may be able to tell us how far we are justified in using the data as we do.

E. J. R.

HARPENDEN
January, 1912

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CHAPTER I

HISTORICAL AND INTRODUCTORY

In all ages the growth of plants has interested thoughtful men. The mystery of the change of an apparently lifeless seed to a vigorous growing plant never loses its freshness, and constitutes, indeed, no small part of the charm of gardening. The economic problems are of vital importance, and become more and more urgent as time goes on and populations increase and their needs become more complex.

There was an extensive literature on agriculture in Roman times which maintained a pre-eminent position until comparatively recently. In this we find collected many of the facts which it has subsequently been the business of agricultural experts to classify and explain. The Roman literature was collected and condensed into one volume about the year 1240 by a senator of Bologna, Petrus Crescentius, whose book[1] was one of the most popular treatises on agriculture of any time, being frequently copied, and in the early days of printing, passing through many editions—some of them very handsome, and ultimately giving rise to the large standard European treatises of the sixteenth and seventeenth centuries. Many other agricultural books appeared in the fifteenth and early sixteenth centuries, notably in Italy, and later in France. In some of these are found certain ingenious speculations that have been justified by later work. Such, for instance, is Palissy's remarkable statement in 1563: "You will admit that when you bring dung into the field it is to return to the soil something that has been taken away. . . . When a plant is burned it is reduced to a salty ash called alcaly by apothecaries and philosophers. . . . Every sort of plant without exception contains some kind of salt. Have you not seen certain labourers when sowing a field with wheat for the second year in succession, burn the unused wheat straw which had been taken from the field? In the ashes will be found the salt that the straw took out of the soil; if this is put back the soil is improved. Being burnt on the ground it serves as manure because it returns to the soil those substances that had been taken away." But for every speculation that has been confirmed will be found many that have not, and the beginnings of agricultural chemistry must be sought later, when men had learnt the necessity for carrying on experiments.

[1] *De agricultura vulgare*, Augsburg, 1471, and many subsequent editions.

The Search for the "Principle" of Vegetation, 1630–1750

It was probably very early discovered that manures, composts, dead animal bodies, and parts of animals, such as blood, all increased the fertility of the land; and this was the basis of the ancient saying that "Corruption is the Mother of Vegetation". Yet the early investigators consistently ignored this ancient wisdom when they sought for the "principle" of vegetation to account for the phenomena of soil fertility and plant growth. Thus the great Francis Bacon, Lord Verulam, believed that water formed the "principal nourishment" of plants, the purpose of the soil being to keep them upright and protect them from excessive cold or heat, though he also considered that each plant drew a "particular juyce" from the soil for its sustenance, thereby impoverishing the soil for that particular plant and similar ones, but not necessarily for other plants. Van Helmont (1577–1644) regarded water as the sole nutrient for plants, and his son thus records his famous Brussels experiment: "I took an earthen vessel in which I put 200 pounds of soil dried in an oven, then I moistened with rain-water and pressed hard into it a shoot of willow weighing 5 pounds. After exactly five years the tree that had grown up weighed 169 pounds and about three ounces. But the vessel had never received anything but rain-water or distilled water to moisten the soil when this was necessary, and it remained full of soil, which was still tightly packed, and, lest any dust from outside should get into the soil, it was covered with a sheet of iron coated with tin but perforated with many holes. I did not take the weight of the leaves that fell in the autumn. In the end I dried the soil once more and got the same 200 pounds that I started with, less about two ounces. Therefore the 164 pounds of wood, bark, and root arose from the water alone."[1]

The experiment is simple and convincing, and satisfied Robert Boyle,[2] who repeated it with "squash, a kind of Indian pompion" and obtained similar results. Boyle further distilled the plants and concluded, quite justifiably from his premises, that the products obtained, "salt, spirit, earth, and even oil (though that be thought of all bodies the most opposite to water), may be produced out of water". Nevertheless, the conclusion is incorrect, because two factors had escaped Van Helmont's notice—the parts played by the air and by the missing two ounces of soil. But the history of this experiment is thoroughly typical of experiments in agricultural chemistry generally: in no other subject is it so easy to overlook a vital factor and draw from good

[1] *Ortus medicinae*, pp. 84–90. *Complexionum atque mistionum elementalium figmentum*, Amsterdam, 1652.

[2] *The sceptical chymist*, Pt. II (1661).

experiments a conclusion that appears to be absolutely sound, but is in reality entirely wrong.

Some years later J. R. Glauber[1] set up the hypothesis that saltpetre is the "principle" of vegetation. Having obtained saltpetre from the earth cleared out from cattle sheds, he argued that it must have come from the urine or droppings of the animals, and must, therefore, be contained in the animal's food, i.e. in plants. He also found that additions of saltpetre to the soil produced enormous increases in crop. He connected these two observations and supposed that saltpetre is the essential principle of vegetation. The fertility of the soil and the value of manures (he mentions dung, feathers, hair, horn, bones, cloth cuttings) are entirely due to saltpetre.

This view was supported by John Mayow's experiments.[2] He estimated the amounts of nitre in the soil at different times of the year, and showed that it occurs in greatest quantity in spring when plants are just beginning to grow, but is not to be found "in soil on which plants grow abundantly, the reason being that all the nitre of the soil is sucked out by the plants". J. A. Külbel,[3] on the other hand, regarded a *magma unguinosum* obtainable from humus as the "principle" sought for.

The most accurate work in this period was published by John Woodward[4] in a remarkable paper. Setting out from the experiments of Van Helmont and of Boyle, but apparently knowing nothing of the work of Glauber and of Mayow, he grew spearmint in water obtained from various sources with the following results among others:

Source of water	Weight of plants		Gained in 77 days	Expense of water (i.e. trans-piration)	Proportion of increase of plant to expense of water
	When put in	When taken out			
	grains	grains	grains	grains	
Rain-water . .	28¼	45¾	17½	3004	1 to 171 2/3 5
River Thames . .	28	54	26	2493	1 to 95 2/2 3/6
Hyde Park conduit .	110	249	139	13140	1 to 94 74/139
Hyde Park conduit plus ½ oz. garden mould .	92	376	284	14950	1 to 52 182/284

Now all these plants had abundance of water, therefore all should have made equal growth had nothing more been needed. The amount

[1] *Des Teutschlandts Wohlfart* (*Erster Theil*), *das dritte Capittel. De concentratione Vegetabilium, Miraculum Mundi*, Amsterdam, 1656.

[2] *Tractatus quinque medico physici* (1674) (*Alembic Club Reprint*, Edinburgh, 1907).

[3] *Cause de la fertilité des terres*, Bordeaux, 1741.

[4] *Phil. Trans. Roy. Soc.*, 1699, **21**, 382.

of growth, however, increased with the impurity of the water. "Vegetables", he concludes, "are not formed of water, but of a certain peculiar terrestrial matter. It has been shown that there is a considerable quantity of this matter contained in rain, spring and river water, that the greatest part of the fluid mass that ascends up into plants does not settle there but passes through their pores and exhales up into the atmosphere: that a great part of the terrestrial matter, mixed with the water, passes up into the plant along with it, and that the plant is more or less augmented in proportion as the water contains a greater or less quantity of that matter; from all of which we may reasonably infer, that earth, and not water, is the matter that constitutes vegetables."

He discusses the use of manures and the fertility of the soil from this point of view, attributing the well-known falling off in crop yield when plants are grown for successive years on unmanured land to the circumstance that "the vegetable matter that it at first abounded in being extracted from it by those successive crops, is most of it borne off. . . . The land may be brought to produce another series of the same vegetables, but not until it is supplied with a new fund of matter, of like sort with that it at first contained; which supply is made several ways, either by the ground's being fallow some time, until the rain has poured down a fresh stock upon it; or by the tiller's care in manuring it." The best manures, he continues, are parts either of vegetables or of animals, which ultimately are derived from vegetables.

In his celebrated text-book of chemistry, H. Boerhaave[1] taught that plants absorb the juices of the earth and then work them up into food. The raw material, the "prime radical juice of vegetables, is a compound from all the three kingdoms, viz. *fossil* bodies and putrified parts of *animals* and *vegetables*". This "we look upon as the *chyle of the plant*; being chiefly found in the first order of vessels, viz. in the roots and the body of the plant, which answers to the stomach and intestines of an animal".

For many years no such outstanding work as that of Glauber and Woodward was published, if we except Stephen Hales's *Vegetable Staticks* in 1727, the interest of which is physiological rather than agricultural.[2] Advances were, however, being made in agricultural practice. One of the most important was the introduction of the drill and the horse hoe by Jethro Tull, an Oxford man of a strongly practical turn of mind, who insisted on the vital importance of getting the soil into a fine, crumbly state for plant growth. Tull was more than an inventor; he discussed in most picturesque language the sources of fertility in the

[1] *A new method of chemistry*, London, 1727.
[2] He shows, however, that air is "wrought into the composition" of plants.

soil.[1] In his view it was not the juices of the earth, but the very minute particles of soil loosened by the action of moisture, that constituted the "proper pabulum" of plants. The pressure caused by the swelling of the growing roots forced these particles into the "lacteal mouths of the roots", where they entered the circulatory system. All plants lived on these particles, i.e. on the same kind of food; it was incorrect to assert, as some had done, that different kinds of plants fed as differently as horses and dogs, each taking its appropriate food and no other. Plants will take in anything that comes their way, good or bad. A rotation of crops is not a necessity, but only a convenience. Conversely, any soil will nourish any plant if the temperature and water supply are properly regulated. Hoeing increased the surface of the soil or the "pasture of the plant", and also enabled the soil better to absorb the nutritious vapours condensed from the air. Dung acted in the same way, but was more costly and less efficient.

So much were Tull's writings esteemed, Cobbett tells us, that they were "plundered by English writers not a few and by Scotch in whole banditti".

The position at the end of this period cannot better be summed up than in Tull's own words: "It is agreed that all the following materials contribute in some manner to the increase of plants, but it is disputed which of them is that very increase or food: (1) nitre, (2) water, (3) air, (4) fire, (5) earth."

The Search for Plant Nutrients

I. THE PHLOGISTIC PERIOD, 1750–1800

Great interest was taken in agriculture in this country during the latter half of the eighteenth century. "The farming tribe", writes Arthur Young during this period, "is now made up of all ranks, from a duke to an apprentice." Many experiments were conducted, facts were accumulated, books written, and societies formed for promoting agriculture. The Edinburgh Society, established in 1755 for the improvement of arts and manufactures, induced Francis Home[2] "to try how far chymistry will go in settling the principles of agriculture". The whole art of agriculture, he says, centres in one point: the nourishing of plants. Investigation of fertile soils showed that they contain oil, which is therefore a food of plants. But when a soil has been exhausted by cropping, it recovers its fertility on exposure to air,[3] which therefore supplies another food. Home made pot experiments to

[1] *Horse Hoeing Husbandry*, London, 1731.
[2] *The principles of agriculture and vegetation*, Edinburgh, 1757.
[3] Recorded by most early writers, e.g. Evelyn (*Terra, a philosophical discourse of earth*, 1674).

ascertain the effect of various substances on plant growth. "The more they (i.e. farmers) know of the effects of different bodies on plants, the greater chance they have to discover the nourishment of plants, at least this is the only road." Saltpetre, Epsom salt, vitriolated tartar (i.e. potassium sulphate) all lead to increased plant growth, yet they are three distinct salts. Olive oil was also useful. It is thus clear that plant food is not one thing only, but several; he enumerates six: air, water, earth, salts of different kinds, oil, and fire in a fixed state. As further proof he shows that "all vegetables and vegetable juices afford those very principles, and no other, by all the chymical experiments which have yet been made on them with or without fire".

The book is a great advance on anything that had gone before it, not only because it recognises that plant nutrition depends on several factors, but because it indicates so clearly the two methods to be followed in studying the problem—pot cultures and plant analysis. Subsequent investigators, J. G. Wallerius,[1] the Earl of Dundonald[2] and R. Kirwan[3] added new details but no new principles. The problem, indeed, was carried as far as was possible until further advances were made in plant physiology and in chemistry. The writers just mentioned are, however, too important to be passed over completely. Wallerius, in 1761, professor of chemistry at Upsala, after analysing plants to discover the materials on which they live, and arguing that *Nutritio non fieri potest a rebus heterogeneis, sed homogeneis*, concludes that humus, being *homogeneous*, is the source of their food—the *nutritiva*—while the other soil constituents are *instrumentalia*, making the proper food mixture, dissolving and attenuating it, till it can enter the plant root. Thus chalk and probably salts help in dissolving the "fatness" of the humus. Clay helps to retain the "fatness" and prevent it being washed away by rain: sand keeps the soil open and pervious to air. The Earl of Dundonald, in 1795, adds alkaline phosphates to the list of nutritive salts, but he attaches chief importance to humus as plant food. The "oxygenation" process going on in the soil makes the organic matter insoluble and therefore useless for the plant; lime, "alkalis and other saline substances" dissolve it and change it to plant food; hence these substances should be used alternately with dung as manure. Manures were thus divided, as by Wallerius, into two classes: those that afford plant food, and those that have some indirect effect.

Throughout this period it was believed that plants could generate alkalis. "Alkalis", wrote Kirwan in 1796, "seem to be the product of

[1] *Agriculturae Fundamenta Chemica: Akerbrukets Chemiska Grunder*, Upsala, 1761.

[2] *A treatise showing the intimate connection that subsists between agriculture and chemistry, etc.*, London, 1795.

[3] *The manures most advantageously applicable to the various sorts of soils and the cause of their beneficial effects in each particular instance*, 4th ed., London, 1796.

the vegetable process, for either none, or scarce any, is found in the soils, or in rain water." In like manner Lampadius thought he had proved that plants could generate silica. The theory that plants agreed in all essentials with animals was still accepted by many men of science; some interesting developments were made by Erasmus Darwin.[1]

Between 1770 and 1800 work was done on the effects of vegetation on air that was destined to revolutionise the ideas of the function of plants in the economy of nature, but its agricultural significance was not recognised until later. Joseph Priestley,[2] knowing that the atmosphere becomes vitiated by animal respiration, combustion, putrefaction, etc., and realising that some natural purification must go on, or life would no longer be possible, was led to try the effect of sprigs of living mint on vitiated air. He found that the mint made the air purer, and concludes "that plants, instead of affecting the air in the same manner with animal respiration, reverse the effects of breathing, and tend to keep the atmosphere pure and wholesome, when it is become noxious in consequence of animals either living, or breathing, or dying, and putrefying in it". But he had not yet discovered oxygen, and so could not give precision to his discovery: and when, later on, he did discover oxygen and learn how to estimate it, he unfortunately failed to confirm his earlier results because he overlooked a vital factor, the necessity of light. He was therefore unable to answer Scheele, who had insisted that plants, like animals, vitiate the air. It was Jan Ingen-Housz[3] who reconciled both views and showed that purification goes on in light only, whilst vitiation takes place in the darkness. Jean Senebier at Geneva had also arrived at the same result. He also studied the converse problem—the effect of air on the plant, and in 1782[4] argued that the increased weight of the tree in Van Helmont's experiment (p. 2) came from the fixed air. "Si donc l'air fixe, dissous dans l'eau de l'atmosphère, se combine dans la parenchyme avec la lumière et tous les autres éléments de la plante; si le phlogistique de cet air fixe est sûrement précipité dans les organes de la plante, si ce précipité reste, comme on le voit, puisque cet air fixe sort des plantes sous la forme d'air déphlogistiqué, il est clair que l'air fixe, combiné dans la plante avec la lumière, y laisse une matière qui n'y seroit pas, et mes expériences sur l'étiolement suffisent pour le démontrer." Later on Senebier translated his work into the modern terms of Lavoisier's system.

[1] *Phytologia, or the philosophy of agriculture and gardening*, London, 1800.
[2] *Experiments and observations on different kinds of air*, London, 1775.
[3] *Experiments upon vegetables, discovering their great power of purifying common air in the sunshine and of injuring in the shade and at night*, London, 1779.
[4] *Mémoires Physico-chimiques*, 1782.

2. THE MODERN PERIOD, 1800–60

(*a*) *The Foundation of Plant Physiology.* We have seen that Home in 1757 pushed his inquiries as far as the methods in vogue would permit, and in consequence no marked advance was made for forty years. A new method was wanted before further progress could be made, or before the new idea introduced by Senebier could be developed. Fortunately, this was soon forthcoming. To Théodore de Saussure, in 1804,[1] son of the well-known de Saussure of Geneva, is due the quantitative experimental method which more than anything else has made modern agricultural chemistry possible: which formed the basis of subsequent work by Boussingault, Liebig, Lawes and Gilbert, and, indeed, still remains our safest method of investigation. Senebier tells us that the elder de Saussure was well acquainted with his work, and it is therefore not surprising that the son attacked two problems that Senebier had also studied—the effect of air on plants and the nature and origin of salts in plants. De Saussure grew plants in air or in known mixtures of air and carbon dioxide, and measured the gas changes by eudiometric analysis and the changes in the plant by "carbonisation". He was thus able to demonstrate the central fact of plant respiration—the absorption of oxygen and the evolution of carbon dioxide, and further to show the decomposition of carbon dioxide and evolution of oxygen in light. Carbon dioxide in small quantities was a vital necessity for plants, and they perished if it was artificially removed from the air. It furnished them not only with carbon, but also with some oxygen. Water is also decomposed and fixed by plants. On comparing the amount of dry matter gained from these sources with the amount of material that can enter through the roots even under the most favourable conditions, he concludes that the soil furnished only a very small part of the plant food. Small as it is, however, this part is indispensable: it supplies nitrogen—*une partie essentielle des végétaux*—which, as he had shown, was not assimilated direct from the air; and also ash constituents, *qui peuvent contribuer à former, comme dans les animaux, leur parties solides ou osseuses.* Further, he shows that the root is not a mere filter allowing any and every liquid to enter the plant; it has a special action and takes in water more readily than dissolved matter, thus effecting a concentration of the solution surrounding it; different salts, also, are absorbed to a different extent. Passing next to the composition of the plant ash, he shows that it is not constant, but varies with the nature of the soil and the age of the plant; it consists mainly, however, of alkalis and phosphates. All the constituents of the ash occur in humus. If a plant is grown from seed in water there is no gain in ash: the amount found at the end of the

[1] *Recherches chimiques sur la végétation*, Paris, 1804.

plant's growth is the same as was present in the seed excepting for a relatively small amount falling on the plant as dust. Thus he disposes finally of the idea that the plant *generated* potash.

After the somewhat lengthy and often wearisome works of the earlier writers it is very refreshing to turn to de Saussure's concise and logical arguments and the ample verification he gives at every stage. But for years his teachings were not accepted, nor were his methods followed.

The two great books on agricultural chemistry then current still belonged to the old period. A. von Thaer and Humphry Davy, while much in advance of Wallerius, the text-book writer of 1761, nevertheless did not realise the fundamental change introduced by de Saussure; it has always been the fate of agricultural science to lag behind pure science. Thaer published his *Grundsätze de rationellen Landwirtschaft* in 1809–12: it had a great success on the Continent as a good, practical hand-book, and was translated into English as late as 1844 by Cuthbert Johnson. In it he adopted the prevailing view that plants draw their carbon and other nutrients from the soil humus. "Die Fruchtbarkeit des Bodens", he says, "hängt eigentlich ganz vom Humus ab. Denn ausser Wasser ist er es allein, der den Pflanzen Nahrung gibt. So wie der Humus eine Erzeugung des Lebens ist, so ist er auch eine Bedingung des Lebens. Er gibt den Organismen die Nahrung. Ohne ihn lässt sich kein individuelles Leben denken." Humphry Davy's book[1] grew out of the lectures which he gave annually at the Royal Institution on agricultural chemistry between 1802 and 1812; it forms the last text-book of the older period. Whilst no great advance was made by Davy himself he carefully sifted the facts and hypotheses of previous writers, and gives us an account, which, however defective in places, represents the best accepted knowledge of the time, set out in the new chemical language. His great name gave the subject an importance it would not otherwise have had.[2] He did not accept de Saussure's conclusion that plants obtain their carbon chiefly from the carbonic acid of the air: some plants, he says, appear to be supplied with carbon chiefly from this source, but in general he supposes the carbon to be taken in through the roots. Oils are good manures because of the carbon and hydrogen they contain; soot is valuable, because its carbon is "in a state in which it is capable of being rendered soluble by the action of oxygen and water". Lime is useful because it dissolves hard vegetable matter. Once the organic matter has dissolved there is no advantage in letting it decompose further: putrid urine is less useful as manure than fresh

[1] *Elements of agricultural chemistry*, London, 1813.

[2] Thus Charles Lamb, *Essays of Elia* (1820–3) in the "Old and New Schoolmaster", writes: "The modern schoolmaster is required to know a little of everything because his pupil is required not to be entirely ignorant of anything. He is to know something of pneumatics, of chemistry, the quality of soils, etc. . . ."

urine, whilst it is quite wrong to cause farmyard manure to ferment before it is applied to the land. All these ideas have been given up, and indeed there never was any sound experimental evidence to support them. 'It is even arguable that they would not have persisted so long as they did had it not been for Davy's high reputation. His insistence on the importance of the physical properties of soils—their relationship to heat and to water—was more fortunate and marks the beginning of soil physics, afterwards developed considerably by Gustav Schübler.[1] On the Continent, to an even greater extent than in England, it was held that plants drew their carbon and other nutrients from the soil humus, a view supported by the very high authority of J. J. Berzelius.[2]

(*b*) *The Foundation of Agricultural Science.* Hitherto experiments had been conducted either in the laboratory or in small pots: about 1834, however, J. B. Boussingault, who was already known as an adventurous traveller in South America, began a series of field experiments on his farm at Bechelbronn in Alsace. These were the first of their kind: to Boussingault, therefore, belongs the honour of having introduced the method by which the new agricultural science was to be developed. He reintroduced the quantitative methods of de Saussure, weighed and analysed the manures used and the crop obtained, and at the end of the rotation drew up a balance sheet, showing how far the manures had satisfied the needs of the crop and how far other sources of supply —air, rain and soil—had been drawn upon. The results of one experiment are given in Table 1.[3] At the end of the period the soil had returned to its original state of productiveness, hence the dry matter, carbon, hydrogen and oxygen not accounted for by the manure must have been supplied by the air and rain, and not by the soil. On the other hand, the manure afforded more mineral matter than the crop took off, the balance remaining in the soil. Other things being equal, he argued that the best rotation is one which yields the greatest amount of organic matter over and above what is present in the manure. No fewer than five rotations were studied, but it will suffice to set out only the nitrogen statistics (Table 2), which show a marked gain of nitrogen when the newer rotations are adopted, but not where wheat only is grown.

Now the rotation has not impoverished the soil, hence he concludes that "l'azote peut entrer directement dans l'organisme des plantes, si leur parties vertes sont aptes à le fixer". Boussingault's work covers the whole range of agriculture and deals with the composition of crops at different stages of their growth with soils, and with problems in

[1] *Grundsätze der Agrikulturchemie in näherer Beziehung auf land- und fortswirtschaftliche Gewerbe*, Leipzig, 1838.

[2] *Traité de chimie*, Brussels, 1838.

[3] *Ann. Chim. Phys.* (III), 1841, **1**, 208.

TABLE 1

Statistics of a Rotation

	Weight in kg. per hectare of					
	Dry matter	Carbon	Hydrogen	Oxygen	Nitrogen	Mineral matter
1. Beets	3172	1357·7	184·0	1376·7	53·9	199·8
2. Wheat	3006	1431·6	164·4	1214·9	31·3	163·8
3. Clover hay	4029	1909·7	201·5	1523·0	84·6	310·2
4. Wheat	4208	2004·2	230·0	1700·7	43·8	229·3
Turnips (catch crop)	716	307·2	39·3	302·9	12·2	54·4
5. Oats	2347	1182·3	137·3	890·9	28·4	108·0
Total during rotation	17478	8192·7	956·5	7009·0	254·2	1065·5
Added in manure.	10161	3637·6	426·8	2621·5	203·2	3271·9
Difference not accounted for taken from air, rain or soil	+7317	+4555·1	+529·7	+4387·5	+51·0	−2206·4

1000 kg. per hectare = 16 cwt. per acre

TABLE 2

Nitrogen Statistics of Various Rotations

Rotation	Kg. per hectare			
	Nitrogen in manure	Nitrogen in crop	Excess in crop over that supplied in manure	
			Per rotation	Per annum
(1) Potatoes, (2) wheat, (3) clover, (4) wheat, turnips,[1] (5) oats	203·2	250·7	47·5	9·5
(1) Beets, (2) wheat, (3) clover, (4) wheat, turnips,[1] (5) oats	203·2	254·2	51·0	10·2
(1) Potatoes, (2) wheat, (3) clover, (4) wheat, turnips,[1] (5) peas, (6) rye	243·8	353·6	109·8	18·3
Jerusalem artichokes, two years	188·2	274·2	86·0	43·0[2]
(1) Dunged fallow, (2) wheat, (3) wheat	82·8	87·4	4·6	1·5
Lucerne, five years	224·0	1078·0	854·0	170·8

[1] Catch crop, i.e. taken in autumn after the wheat.

[2] This crop does not belong to the leguminosae, but it is possible that the nitrogen came from the soil, and that impoverishment was going on.

animal nutrition. Unfortunately the classic farm of Bechelbronn did not remain a centre of agricultural research and the experiments came to an end after the war of 1870. Some of the work was summarised by J. B. A. Dumas and Boussingault[1] in a very striking essay that has been curiously overlooked by agricultural chemists.

During this period (1830–40) Carl Sprengel was studying the ash constituents of plants, which he considered were probably essential to nutrition.[2] Schübler was working at soil physics, and a good deal of other work was quietly being done. No particularly important discoveries were being made, no controversies were going on, and no great amount of interest was taken in the subject.

But all this was changed in 1840 when Liebig's famous report to the British Association[3] upon the state of organic chemistry, published as *Chemistry in its Application to Agriculture and Physiology* in 1840, came like a thunderbolt upon the world of science. With polished invective and a fine sarcasm he holds up to scorn the plant physiologists of his day for their continued adhesion, in spite of accumulated evidence, to the view that plants derive their carbon from the soil and not from the carbonic acid of the air. "All explanations of chemists must remain without fruit, and useless, because, even to the great leaders in physiology, carbonic acid, ammonia, acids and bases are sounds without meaning, words without sense, terms of an unknown language, which awake no thoughts and no associations." The experiments quoted by the physiologists in support of their view are all "valueless for the decision of any question". "These experiments are considered by them as convincing proofs, whilst they are fitted only to awake pity." Liebig's ridicule did what neither de Saussure's nor Boussingault's logic had done: it finally killed the humus theory. Only the boldest would have ventured after this to assert that plants derive their carbon from any source other than carbon dioxide, although it must be admitted that we have no proof that plants really do obtain all their carbon in this way. Thirty years later, in fact, L. Grandeau[4] adduced evidence that humus may, after all, contribute something to the carbon supply, and his view found some acceptance in France;[5] for this also, however, convincing proof is lacking. But for the time carbon dioxide was considered to be the sole source of the carbon of plants. Hydrogen and oxygen came from water, and nitrogen from ammonia. Certain mineral substances were essential: alkalis were needed for neutralisation of the acids made by plants in the course of their vital processes, phosphates

[1] *Essai de statique chimique des êtres organisés*, Paris, 1841.
[2] *Chemie für Landwirthe, Forstmänner und Cameralisten*, Göttingen, 1832.
[3] There is no record of this Report ever having been presented to the Association.
[4] *C.R.*, 1872, **74**, 988; *Publication de la Station Agronomique de l'Est*, 1872.
[5] See, for example L. Cailletet (*C.R.*, 1911, **152**, 1215), Jules Lefèvre (ibid., 1905, **141**, 211), and J. Laurent (*Rev. gén. bot.*, 1904, **16**, 14).

were necessary for seed formation, and potassium silicates for the development of grasses and cereals. The evidence lay in the composition of the ash: plants might absorb anything soluble from the soil, but they excreted from their roots whatever was non-essential. The fact of a substance being present was therefore sufficient proof of its necessity.

Plants, Liebig argued, have an inexhaustible supply of carbonic acid in the air. But time is saved in the early stages of plant growth if carbonic acid is being generated in the soil, for it enters the plant roots and affords extra nutrient over and above what the small leaves are taking in. Hence a supply of humus, which continuously yields carbonic acid, is advantageous. Further, the carbonic acid attacks and dissolves some of the alkali compounds of the soil and thus increases the mineral food supply. The true function of humus is to evolve carbonic acid.

The alkali compounds of the soil are not all equally soluble. A weathering process has to go on, which is facilitated by liming and cultivation, whereby the comparatively insoluble compounds are broken down to a more soluble state. The final solution is effected by acetic acid excreted by the plant roots, and the dissolved material now enters the plant.

The nitrogen is taken up as ammonia, which may come from the soil, from added manure, or from the air. In order that a soil may remain fertile it is necessary and sufficient to return in the form of manure the mineral constituents and the nitrogen that have been taken away. When sufficient crop analyses have been made it will be possible to draw up tables showing the farmer precisely what he must add in any particular case.

An artificial manure known as Liebig's patent manure was made up on these lines and placed on the market.

Liebig's book was meant to attract attention to the subject, and it did; it rapidly went through several editions, and as time went on Liebig developed his thesis, and gave it a quantitative form: "The crops on a field diminish or increase in exact proportion to the diminution or increase of the mineral substances conveyed to it in manure." He further adds what afterwards became known as the Law of the Minimum, "by the deficiency or absence of *one* necessary constituent, all the others being present, the soil is rendered barren for all those crops to the life of which *that one* constituent is indispensable". These and other amplifications in the third edition, 1843, gave rise to much controversy. So much did Liebig insist, and quite rightly, on the necessity for alkalis and phosphates, and so impressed was he by the gain of nitrogen in meadow land supplied with alkalis and phosphates alone, and by the continued fertility of some of the fields of Virginia

and Hungary and the meadows of Holland, that he began more and more to regard the atmosphere as the source of nitrogen for plants. Some of the passages of the first and second editions urging the necessity of ammoniacal manures were deleted from the third and later editions. "If the soil be suitable, if it contain a sufficient quantity of alkalis, phosphates, and sulphates, nothing will be wanting. The plants will derive their ammonia from the atmosphere as they do carbonic acid", he writes in the *Farmer's Magazine*.[1] Ash analysis led him to consider the turnip as one of the plants "which contain the least amount of phosphates and therefore require the smallest quantity for their development". These and other practical deductions were seized upon and shown to be erroneous by J. B. Lawes and J. H. Gilbert,[2] who had for some years been conducting vegetation experiments. Lawes does not discuss the theory as such, but tests the deductions Liebig himself draws and finds them wrong. Further trouble was in store for Liebig; his patent manure when tried in practice *had failed*. This was unfortunate, and the impression in England at any rate was, in Philip Pusey's words: "The mineral theory, too hastily adopted by Liebig, namely, that crops rise and fall in direct proportion to the quantity of mineral substances present in the soil, or to the addition or abstraction of these substances which are added in the manure, has received its death-blow from the experiments of Mr. Lawes."

And yet the failure of the patent manure was not entirely the fault of the theory, but only affords further proof of the numerous pitfalls of the subject. The manure was sound in that it contained potassium compounds and phosphates (it ought, of course, to have contained nitrogen compounds), but it was unfortunately rendered insoluble by fusion with lime and calcium phosphate so that it should not too readily wash out in the drainage water. Not till J. T. Way had shown in 1850[3] that *soil precipitates soluble salts of ammonium, potassium and phosphates* was the futility of the fusion process discovered, and Liebig[4] saw the error he had made.

Meanwhile the great field experiments at Rothamsted had been started by Lawes and Gilbert in 1843. These experiments were conducted on the same general lines as those begun earlier by Boussingault, but they have the advantage that they are still going on, having been continued year after year on the same ground without alteration, except in occasional details, since 1852. The mass of data now accumulated is considerable and it is being treated by modern statistical

[1] *Farmer's Magazine*, 1847, **16**, 511. A good summary of Liebig's position is given in his *Familiar letters on chemistry*, 34th letter, 3rd ed., p. 519, 1851.
[2] *J. Roy. Agric. Soc.*, 1847, **8**, 226; 1851, **12**, 1; 1855, **16**, 411.
[3] *J. Roy. Agric. Soc.*, 1850, **11**, 313; 1852, **13**, 123.
[4] *Familiar letters on chemistry*, 3rd ed., London, 1851.

methods. Certain conclusions are so obvious, however that they can be drawn on mere inspection of the data. By 1855 the following points were definitely settled:[1]

1. Crops require phosphates and salts of the alkalis, but the composition of the ash does not afford reliable information as to the amounts of each constituent needed, e.g. turnips require large amounts of phosphates, although only little is present in their ash. Some of the results are:

Composition of ash, per cent (1860 crop)—		Yield of turnips, tons per acre (1843)—	
K_2O	44·8	Unmanured	4·5
P_2O_5	7·9	Superphosphate	12·8
		,, + potassic salts	11·9

2. Non-leguminous crops require a supply of some nitrogenous compounds, nitrates and ammonium salts being almost equally good. Without an adequate supply no increases of growth are obtained, even when ash constituents are added. The amount of ammonia obtainable from the atmosphere is insufficient for the needs of crops. Leguminous crops behave abnormally.

3. Soil fertility may be maintained for some years at least by means of artificial manures.

4. The beneficial effect of fallowing lies in the increase brought about in the available nitrogen compounds in the soil.

Although many of Liebig's statements were shown to be wrong, the main outline of his theory as first enunciated stands. It is no detraction that de Saussure had earlier published a somewhat similar, but less definite view of nutrition: Liebig had brought matters to a head and made men look at their cherished, but unexamined, convictions. The effect of the stimulus he gave can hardly be over-estimated, and before he had finished, the essential facts of plant nutrition were settled and the lines were laid down along which scientific manuring was to be developed. The water cultures of Knop and other plant physiologists showed conclusively that potassium, magnesium, calcium, iron, phosphorus, along with sulphur, carbon, nitrogen, hydrogen and oxygen are all necessary for plant life. The list differs from Liebig's only in the addition of iron and the withdrawal of silica; but even silica, although not strictly essential, is advantageous for the nutrition of cereals.

In two directions, however, the controversies went on for many years.

[1] Lawes and Gilbert's papers are collected in ten volumes of *Rothamsted Memoirs*, and the general results of their experiments are summarised by Hall in *The Book of the Rothamsted Experiments*. A detailed investigation of the early experiments of Lawes in their relation to the discovery of superphosphate has been made by Max Speter in *Superphosphate*, 1935, **8**.

Farmers were slow to believe that "chemical manures" could ever do more than stimulate the crop, and declared they must ultimately exhaust the ground. The Rothamsted plots falsified this prediction; manured year after year with the same substances and sown always with the same crops, they even now, after a hundred years of chemical manuring, continue to produce good crops, although secondary effects have sometimes set in. In France the great missionary was Georges Ville,[1] whose lectures were given at the experimental farm at Vincennes during 1867 and 1874–5. He went even further than Lawes and Gilbert, and maintained that artificial manures were not only more remunerative than dung, but were the only way of keeping up fertility. In recommending mixtures of salts for manure he was not guided by ash analysis but by field trials. For each crop one of the four constituents, nitrogen compounds, phosphates, lime and potassium compounds (he did not consider it necessary to add any others to his manures) was found by trial to be more wanted than the others and was therefore called the "dominant" constituent. Thus for wheat he obtained the following results, and therefore concluded that on his soil wheat required a good supply of nitrogen, less phosphate, and still less potassium:

	Crop per acre bushels
Normal manure	43
Manure without lime	41
„ „ potash	31
„ „ phosphate	26½
„ „ nitrogen	14
Soil without manure	12

Other experiments of the same kind showed that nitrogen was the dominant for all cereals and beetroot, potassium for potatoes and vines, phosphates for the sugar-cane. An excess of the dominant constituent was always added to the crop manure. The composition of the soil had to be taken into account, but soil analysis was no good for the purpose. Instead he drew up a simple scheme of plot trials to enable farmers to determine for themselves just what nutrient was lacking in their soil. His method was thus essentially empirical, but it still remains the best we have: his view that chemical manures are always better and cheaper than dung is, however, too narrow and has not survived.

The second controversy dealt with the source of nitrogen in plants. Priestley had stated that a plant of *Epilobium hirsutum* placed in a small

[1] *On artificial manures, their chemical selection and scientific application to agriculture.* Trans. by W. Crookes, London, 1879.

vessel absorbed during the course of the month seven-eighths of the air present. De Saussure, however, denied that plants assimilated gaseous nitrogen. J. B. Boussingault's pot experiments[1] showed that peas and clover could get nitrogen from the air while wheat could not, and his rotation experiments emphasised this distinction. He himself did not make as much of this discovery as he might have done, but J. B. A. Dumas and Boussingault[2] fully realised its importance.

Liebig, as we have seen, maintained that ammonia, but not gaseous nitrogen, was taken up by plants, a view confirmed by Lawes, Gilbert and E. Pugh[3] in the most rigid demonstration that had yet been attempted. Plants of several natural orders, including the leguminosae, were grown in surroundings free from ammonia or any other nitrogen compound. The soil was burnt to remove all trace of nitrogen compounds, while the plants were kept throughout the experiment under glass shades, but supplied with washed and purified air and with pure water. In spite of the ample supply of mineral food the plants languished and died: the conclusion seemed irresistible that plants could not utilise gaseous nitrogen. For all non-leguminous crops this conclusion agreed with the results of field trials. But there remained the very troublesome fact that leguminous crops required no nitrogenous manure and yet they contained large quantities of nitrogen, and also enriched the soil considerably in this element. Where had the nitrogen come from? The amount of combined nitrogen brought down by the rain was found to be far too small to account for the result. For years experiments were carried on, but the problem remained unsolved. Looking back over the papers[4] one can see how very close some of the older investigators were to the discovery of the cause of the mystery: in particular J. Lachmann[5] carefully examined the structure of the nodules, which he associated with the nutrition of the plant, and showed that they contained "vibrionenartige" organisms. His paper, however, was published in an obscure journal and attracted little attention. W. O. Atwater in 1881 and 1882 showed that peas acquired large quantities of nitrogen from the air, and later suggested that they might "favour the action of nitrogen-fixing organisms".[6] But he was too busily engaged to follow the matter up, and once again an investigation in agricultural chemistry had been brought to a standstill for want of new methods of attack.

[1] *Ann. Chim. Phys.* (II), 1838, **67**, 5; **69**, 353; 1856 (III), **46**, 5.
[2] *Essai de statique chimique des êtres organisés*, Paris, 1841.
[3] *Phil. Trans.*, 1861, **151**, 431; 1889, **180** A, 1; *J. Roy. Agric. Soc.*, 1891, ser. 3, **2**, 657.
[4] A summary of the voluminous literature is contained in Löhnis's *Handbuch der landw. Bakteriologie*, pp. 646 *et seq.*
[5] *Mitt. Landw. Lehranst.*, Poppelsdorf, 1858, **1**. Reprinted in *Zbl. Agrik. Chem.*, 1891, **20**, 837.
[6] *Amer. Chem. J.*, 1885, **6**, 365; **8**, 327.

The Beginnings of Soil Bacteriology

It had been a maxim with the older agricultural chemists that "corruption is the mother of vegetation". Animal and vegetable matter had long been known to decompose with formation of nitrates: indeed nitre beds made up from such decaying matter were the recognised source of nitrates for the manufacture of gunpowder during the European wars of the seventeenth and eighteenth centuries.[1] No satisfactory explanation of the process had been offered, although the discussion of rival hypotheses continued up till 1860, but the conditions under which it worked were known and on the whole fairly accurately described.

No connection was at first observed between nitrate formation and soil productiveness. Liebig[2] rather diverted attention from the possibility of tracing what now seems an obvious relationship by regarding ammonia as the essential nitrogenous plant nutrient, though he admitted the possible suitability of nitrates. Way came much nearer to the truth. In 1856 he showed that nitrates were formed in soils to which nitrogenous fertilisers were added. Unfortunately he failed to realise the significance of this discovery. He was still obsessed with the idea that ammonia was essential to the plant, and he believed that ammonia, unlike other nitrogen compounds, could not change to nitrate in the soil, but was absorbed by the soil by the change he had already described (p. 14). But he only narrowly missed making an important advance in the subject, for after pointing out that nitrates are comparable with ammonium salts as fertilisers he writes: "Indeed the French chemists are going further, several of them now advocating the view that it is in the form of nitric acid that plants make use of compounds of nitrogen. With this view I do not myself at present concur: and it is sufficient here to admit that nitric acid in the form of nitrates has at least a very high value as a manure."

It was not till ten years later, and as a result of work by plant physiologists, that the French view prevailed over Liebig's, and agricultural investigators recognised the importance of nitrates to the plant and of nitrification to soil fertility. It then became necessary to discover the cause of nitrification.

During the 'sixties and 'seventies great advances were being made in bacteriology, and it was definitely established that bacteria bring about putrefaction, decomposition and other changes; it was therefore conceivable that they were the active agents in the soil, and that the

[1] *Instructions sur l'établissement des nitrières, publié par les Régisseurs généraux des Poudres et Salpètre*, Paris, 1777.

[2] *Principles of agricultural chemistry with special reference to the late researches made in England*, London, 1855.

process of decomposition there taking place was not the purely chemical "eremacausis" Liebig had postulated. Pasteur himself had expressed the opinion that nitrification was a bacterial process. The new knowledge was first brought to bear on agricultural problems by Th. Schloesing and A. Müntz[1] during a study of the purification of sewage water by land filters. A continuous stream of sewage was allowed to trickle down a column of sand and limestone so slowly that it took eight days to pass. For the first twenty days the ammonia in the sewage was not affected, then it began to be converted into nitrate; finally all the ammonia was converted during its passage through the column, and nitrates alone were found in the issuing liquid. Why, asked the authors, was there a delay of twenty days before nitrification began? If the process were simply chemical, oxidation should begin at once. They therefore examined the possibility of bacterial action and found that the process was entirely stopped by a little chloroform vapour, but could be started again after the chloroform was removed by adding a little turbid extract of dry soil. Nitrification was thus shown to be due to micro-organisms—"organised ferments", to use their own expression.

R. Warington[2] had been investigating the nitrates in the Rothamsted soils, and at once applied the new discovery to soil processes. He showed that nitrification in the soil is stopped by chloroform and carbon disulphide; further, that solutions of ammonium salts could be nitrified by adding a trace of soil. By a careful series of experiments described in his four papers to the Chemical Society he found that there were two stages in the process and two distinct organisms: the ammonia was first converted into nitrite and then to nitrate. But he failed altogether to obtain the organisms, in spite of some years of study, by the gelatin methods then in vogue. However S. Winogradsky,[3] in a brilliant investigation, isolated these two groups of organisms, showing they were bacteria. He succeeded where Warington failed because he realised that carbon dioxide should be a sufficient source of carbon for them, so that they ought to grow on silica gel plates carefully freed from all organic matter; and it was on this medium that he isolated them in 1890.

Warington also established definitely the fact that nitrogen compounds rapidly change to nitrates in the soil, so that whatever compound is supplied as manure, plants get practically nothing but nitrate as food. This closed the long discussion as to the nitrogenous food of non-leguminous plants; in natural conditions they take up nitrates only (or at any rate chiefly), because the activities of the nitrifying organisms leave them no option. The view that plants assimilate gaseous

[1] *C.R.*, 1877, **84**, 301; **85**, 1018; 1878, **86**, 892.
[2] *J. Chem. Soc.*, 1878, **33**, 44; 1879, **35**, 429; 1884, **45**, 637; 1891, **59**, 484.
[3] *Ann. Inst. Pasteur*, 1890, **4**, 213, 257, 760.

nitrogen has from time to time been revived,[1] but it is not generally accepted.

The apparently hopeless problem of the nitrogen nutrition of leguminous plants was soon to be solved. In a striking series of sand cultures H. Hellriegel and H. Wilfarth[2] showed that the growth of non-leguminous plants, barley, oats, etc., was directly proportional to the amount of nitrate supplied, the duplicate pots agreeing satisfactorily; while in the case of leguminous plants no sort of relationship existed and duplicate pots failed to agree. After the seedling stage was passed the leguminous plants grown without nitrate made no further progress for a time, then some of them started to grow and did well, while others failed. This stagnant period was not seen where nitrate was supplied. Two of their experiments are given in Table 3.

TABLE 3

Relation between Nitrogen Supply and Plant Growth

Nitrogen in the calcium nitrate supplied per pot, gm.	none	0·056	0·112	0·168	0·224	0·336
Weight of oats obtained (grain and straw)	0·361 0·419	5·902 5·851 5·287	10·981 10·941	15·997	21·273 21·441	30·175
Weight of peas obtained (grain and straw)	0·551 3·496 5·233	0·978 1·304 4·128	4·915 9·767 8·497	5·619	9·725 6·646	11·352

Analysis showed that the nitrogen contained in the oat crop and sand at the end of the experiment was always a little less than that originally supplied, but was distinctly greater in the case of peas; the gain in three cases amounted to 0·910, 1·242 and 0·789 gm. per pot respectively. They drew two conclusions: (1) the peas took their nitrogen from the air; (2) the process of nitrogen assimilation was conditioned by some factor that did not come into their experiment except by chance. In trying to frame an explanation they connected two facts that were already known. M. Berthelot[3] had made experiments to show that certain micro-organisms in the soil can assimilate gaseous nitrogen. It was known to botanists that the nodules on the

[1] e.g. Th. Pfeiffer and E. Franke, *Landw. Vers.-Stat.*, 1896, **46**, 117; Thos. Jamieson, *Aberdeen Res. Assoc. Repts.*, 1905–8; C. B. Lipman and J. K. Taylor, *J. Franklin Inst., Calif.*, 1924, p. 475.

[2] *Ztschr. Rübenzucker-Ind.*, Beilageheft, 1888.

[3] *C.R.*, 1885, **101**, 775.

roots of leguminosae contained bacteria.[1] Hellriegel and Wilfarth, therefore, supposed that the bacteria in the nodules assimilated gaseous nitrogen, and then handed on some of the resulting nitrogenous compounds to the plant. This hypothesis was shown to be well founded by the following facts:

1. In absence of nitrates peas made only small growth and developed no nodules in sterilised sand; when calcium nitrate was added they behaved like oats and barley, giving regular increases in crop for each increment of nitrates (the discordant results of Table 3 were obtained on unsterilised sand).

2. They grew well and developed nodules in sterilised sand watered with an extract of arable soil.

3. They sometimes did well and sometimes failed when grown without soil extract and without nitrate in *unsterilised* sand, which might or might not contain the necessary organisms. An extract that worked well for peas might be without effect on lupins or serradella. In other words, the organism is specific.

Hellriegel and Wilfarth read their paper and exhibited some of their plants at the Naturforscher-Versammlung at Berlin in 1886. Gilbert was present at the meeting, and on returning to Rothamsted repeated and confirmed the experiments. At a later date Th. Schloesing *fils* and E. Laurent[2] showed that the weight of nitrogen absorbed from the air was approximately equal to the gain by the plant and the soil, and thus finally clinched the evidence.

	Control	Peas	Mustard	Cress	Spurge
Nitrogen lost from the air, mgm.	1·0	134·6	— 2·6	— 3·8	— 2·4
Nitrogen gained by crop and soil, mgm. . . .	4·0	142·4	— 2·5	2·0	3·2

The organism was isolated by M. W. Beijerinck[3] and called *Bacillus radicicola*, but is now known as *Rhizobium*.

Thus another great controversy came to an end, and the discrepancy between the field trials and the laboratory experiments of Lawes, Gilbert and Pugh was cleared up. The laboratory experiments gave the correct conclusion that leguminous plants, like non-leguminous

[1] This had been demonstrated by Lachmann (p. 17) and by M. Woronin (*Mem. Acad. Sci.*, St. Petersburg, 1866, ser. 7, **10**, No. 6). J. Eriksson in 1874 (Doctor's dissertation, abs. in. *Botan. Ztg.*, 1874, **32**, 381) carried on the investigation, while G. Brunchorst in 1885 (*Ber. Deut. Bot. Ges.*, **3**, 241) gave the name "bacteroids".

[2] *Ann. Inst. Pasteur*, 1892, **6**, 65.

[3] *Bot. Ztg.*, 1888, **46**, 725, 741, 757; 1890, **48**, 837.

plants, have themselves no power of assimilating gaseous nitrogen; this power belongs to the bacteria associated with them. But so carefully was all organic matter removed from the soil, the apparatus and the air in endeavouring to exclude all trace of ammonia, that there was no chance of infection with the necessary bacteria. Hence no assimilation could go on. In the field trials the bacteria were active, and here there was a gain of nitrogen.

The general conclusion that bacteria are the real makers of plant food in the soil, and are, therefore, essential to the growth of all plants, was developed by E. Wollny[1] and M. Berthelot.[2] It was supposed to be proved by E. Laurent's[3] experiments. He grew buckwheat on humus obtained from well-rotted dung, and found that plants grew well on the untreated humus, but only badly on the humus sterilised by heat. When, however, soil bacteria were added to the sterilised humus (by adding an aqueous extract of unsterilised soil) good growth took place. The experiment looks convincing, but is really unsound. When a rich soil is heated some substance is formed toxic to plants. The failure of the plants on the sterilised humus was, therefore, not due to absence of bacteria, but to the presence of a toxin. No one has yet succeeded in carrying out this fundamental experiment of growing plants in two soils differing only in that one contains bacteria while the other does not.

The Rise of Modern Knowledge of the Soil, and the Return to Field Studies

Further investigation of soil problems has shown that they are more complex than was at first supposed. Soils can no longer satisfactorily be divided into a few simple groups: sands, clays, loams, etc., according to their particle size; nor can attention be confined to the surface layer. It is necessary to take account of their history. The properties of a soil depend not only on its parent material but also, as shown by the Russian investigator V. V. Dokuchaev[4] in particular, on the climatic, vegetation and other factors to which it has been subjected.

The relations of the plant to the soil are also recognised as highly complex. The older workers had thought of soil fertility as a simple chemical problem; the early bacteriologists thought of it as bacteriological. E. Wollny[5] and F. H. King[6] showed that the physical properties of the soil already studied by Davy and Schübler play a

[1] *Bied. Zbl. Agric. Chem.*, 1884, **13**, 796. [2] *C.R.*, 1888, **106**, 569.
[3] *Bull. Acad. Roy. Belgique*, 1886, **2**, 128. See also E. Duclaux, *C.R.*, 1885, **100**, 66.
[4] *Tchernozème de la Russie d'Europe*, St. Petersburg, 1883.
[5] Papers by himself and his students in *Forschungen auf dem Gebiete der Agrikultur-Physik*, 1878–98. [6] *The Soil*, New York, 1899.

fundamental part in soil fertility. Van Bemmelen showed that soil has colloidal properties, and present-day workers have observed in the soil many of the phenomena investigated in laboratories devoted to the study of colloids. Whitney and Cameron at Washington greatly widened the subject by revealing the importance of the soil solution and introducing the methods and principles of physical chemistry. Russell and Hutchinson at Rothamsted showed that bacterial action alone would not account for the biological phenomena in the soil, but that other organisms are also concerned, and subsequent work in the Rothamsted laboratories and elsewhere has revealed the presence of a complex soil population, the various members of which react on one another and on the growing plant.

The nature of the subject necessitates a departure from the usual procedure. In purely laboratory investigations it is customary to adopt the Baconian method, in which factors are studied one at a time, all others being kept constant except the particular one under investigation. In dealing with soils in natural conditions, however, it is impossible to proceed in this way: climatic factors will not be kept constant, and however careful the effort to ensure equality of conditions there is always the probability, and sometimes the certainty, that the variable factor under investigation is interacting with climatic factors and exerting indirect effects which modify or even obscure the direct effects it is desired to study. Hence, in recent years, statisticians have had to devise methods for dealing with cases where several factors are varying simultaneously.

This increased interest in the soil has shown itself in two directions. The development of soil surveys has encouraged an enormous development of soil studies *in situ*; and the introduction of modern statistical methods has given to field experiments a new value they completely lacked before. In the past, field experiments were always weakened by the unknown errors due to the circumstances that the soil of one plot was never strictly comparable with the soil of another. Modern methods of field plot technique have overcome this difficulty and yield results to which a definite value can be assigned so that the data can be utilised in further investigations.

CHAPTER II

THE FOOD OF PLANTS

GREEN PLANTS SYNTHESISE their food from simple substances taken out of the air and the soil. It is common to speak of these substances as the actual foods: in reality they are the raw materials out of which the food is made. Plants, like all other organisms, have their tissues built out of carbohydrates, fats, proteins and nucleoproteins, and need for the functioning of their tissues a host of enzymes. Hence the plant needs large quantities of carbon, oxygen, hydrogen, nitrogen, phosphorus, and sulphur for building up its tissues; it needs small quantities of at least iron, magnesium, manganese, zinc, copper and boron and usually molybdenum for building up its enzymes; and it needs potassium, sometimes sodium, calcium and often other electrolytes for these or other purposes. Other elements, such as silicon, aluminium and chlorine, may be necessary, and are certainly present in the tissues of all plants grown in the field, though they have not been shown to have essential specific effects on the growth and development of the crop. Carbon dioxide and water are probably the sole source of carbon and hydrogen for most plants; ammonium and nitrate ions are an adequate source of nitrogen, though some leguminous plants can supplement these with nitrogen from the air; and the other elements are usually taken up from the soil as simple inorganic ions.

Carbon dioxide from the air and simple inorganic ions in the soil can certainly supply all the nutrients needed by the plant. But this does not prove that plants in the field obtain all their nutrients from these sources or that their growth may not be improved if they can take up complex substances of vitamin or hormone-like nature. Claims have, in fact, repeatedly been made that other sources of food are necessary if the crop is to make optimum growth, which is sometimes measured by crop yield and sometimes by improvements in its feeding value. In some conditions plants in fact obtain some of their food from other sources. The outer cells of their roots may contain fungal hyphae which extend around or even through the cells and into the soil. This association between root and fungus can be very strongly developed—as, for example, on forest trees growing on poor soil—giving structures known as mycorrhizas, which are described in more detail in Chapter 13. The fungus in this association transfers nutrients, in particular nitrogen and phosphate, from the soil to the root cells, handing them on to these cells as complex substances. There is, however, no critical evidence to

show that this mechanism plays any important part in the nutrition of crops grown on normal arable soils.

Many experiments have been made to see if the performance of a crop can be improved by supplying it either with vitamins or with plant hormones, but the results so far have been inconclusive. It is well established that isolated organs of a plant—such as excised roots—can only be grown in artificial conditions if some of the B vitamins are present, but this is no evidence that plants are unable to synthesise all the vitamins they need. There is, in fact, no well established evidence that adding any vitamin or growth promoting factor to the soil ever improves crop production,[1] or has any appreciable effect on the vitamin content of the plant. This is much more dependent on climate and possibly soil than on manuring. Vitamin C contents in particular seem to be high in years of bright sunshine.[2]

The question whether farmyard manure owes its value as a plant food to any so far unrecognised nutrient, needed only in minute quantities, cannot yet be definitely answered, though the experimental evidence is against any such possibility. Provided the soil conditions around the plant roots—as measured by the air and water supply—are favourable, it appears that the value of farmyard manure—as measured by crop yield—depends only on the amount of nutrients it can supply in simple form to the crop. Naturally, the farmyard manure itself often has an important role in creating a favourable air and water régime around the plant roots, but this effect is not of relevance to this particular question. Farmyard manure can, however, be a very valuable carrier of some minor elements, and in particular additions of farmyard manure may be the easiest way of maintaining an adequate supply of available iron to the plant.[3]

The second question—to which extravagant answers have been given by some workers—is whether the feeding value of the crop, either for animals or humans, is affected by the presence of farmyard manure or composts in the soil. The earlier experimental evidence on this point was conflicting, possibly because of imperfections in experimental technique, but the few recent accurate experiments that have been

[1] For some evidence that vitamin B_1 may be of value, see J. Bonner and J. Greene, *Bot. Gaz.*, 1938, **100**, 226, and 1939, **101**, 491; but D. I. Arnon, *Sci.*, 1940, **92**, 264; C. L. Hamner, *Bot. Gaz.*, 1940, **102**, 156; W. G. Templeman and M. Pollard, *Ann. Bot.*, 1941, **5**, 133; and D. B. Swartz, *Bot. Gaz.*, 1941, **103**, 366, were unable to confirm this. H. Lundegårdh, *Kgl. Lantbr. Akad. Tidskr.*, 1943, **82**, 99, found some evidence that vitamin B_1 in the presence of phosphate and magnesium might be able to increase yields. For a short review of the literature, see R. L. Starkey, *Soil Sci.*, 1944, **57**, 264. For some evidence that indolyl- or naphthyl-acetic acids may be of value, see G. P. McRostie *et al.*, *Canad. J. Res.*, 1938, **16** C, 510, for wheat, A. Dunez, *C.R. Acad. Agric.*, 1946, **32**, 736, and 1947, **33**, 548, for wheat and other farm crops, and H. L. Stier and H. G. du Bay, *Proc. Amer. Soc. Hort. Sci.*, 1939, **36**, 723, for tomatoes. H. L. Pearse reviewed this subject in *Imp. Bur. Hort., Tech. Comm.* 12, 1939.

[2] For cow-peas, M. E. Reid, *Bull. Torrey Bot. Cl.*, 1942, **62**, 204; for tomatoes in England, F. Wokes *et al.*, *Nature*, 1947, **159**, 172.

[3] J. Bonner, *Bot. Gaz.*, 1946, **108**, 267.

made have given no indication that the presence of farmyard manure or compost in a soil has any specific action in increasing the vitamin content[1] or the nutritive value[2] of the plant.

This result appears to be general, for fertilisers also seem to have little effect on the vitamin content of the leaves and roots of crops. However, the carotene and chlorophyll content of grass can be increased a little by nitrogen manuring,[3] as is shown by its darker green colour, and the carotene content of lucerne by boron under some conditions,[4] and of soybean leaves by phosphates.[5] On the other hand, the concentration of vitamin C in the tissues of a crop is often somewhat lowered by any manuring that increases the growth of the crop. Thus L. J. Harris and D. J. Watson[6] found that normal dressings of farmyard manure or sulphate of ammonia lowered the vitamin C content of potato tubers. Again, small potato tubers[7] tend to have higher vitamin C contents than large, and slow-growing leaves of vegetable crops than fast growing.[8]

The plant needs its nutrients for three distinct but overlapping purposes. It must build its protoplasm and form all the enzymes needed for its vital processes and growth, it must build tissues to support and protect its protoplasm, and it must be able to transport nutrients from one organ to another.

The plant's supporting and protecting tissues are built out of polymerised sugar residues such as celluloses, hemicelluloses and pectins, on the one hand, and lignins on the other, though the latter are typically formed as the tissues mature. They also contain inorganic constituents whose functions and chemical combinations are uncertain. Thus graminaceous plants—the grasses and cereals—accumulate considerable quantities of silica in their tissues. Further, many plants accumulate sugars or polymerised sugar residues, for example starch and inulin, as a food reserve in their tissues, but other substances, such as oils and proteins, may also accumulate in them for the same reason. The enzyme systems in the plant are built up out of proteins and nucleoproteins, and thus contain large proportions of nitrogen and phosphate, with some sulphur. They also require certain metals and other elements, and unless the particular metal needed is present, the enzyme cannot function: only very rarely can that particular metal

[1] For a review of this subject, see L. A. Maynard and K. C. Beeson, *Nutr. Abstr.*, 1943, **13**, 155.
[2] D. I. Arnon, H. D. Simms and A. F. Morgan, *Soil Sci.*, 1947, **63**, 129.
[3] B. Thomas and F. E. Moon, *Emp. J. Expt. Agric.*, 1938, **7**, 235.
[4] W. L. Powers, *Proc. Soil Sci. Soc. Amer.*, 1939, **4**, 290.
[5] W. J. Peterson *et al.*, *Amer. Fert.*, 1948, No. 3, 24.
[6] Unpublished observations.
[7] Unpublished observations of J. Meiklejohn.
[8] S. H. Wittiver, R. A. Schroeder and W. A. Albrecht, *Soil Sci.*, 1945, **59**, 329.

be replaced by another without destroying, or at least greatly weakening, the effectiveness of the enzyme. The liquid that transports the various nutrients throughout the plant, either from the roots, the green leaves or the storage organs, also contains inorganic ions. These may be nutrient ions, but they are also regulators of the osmotic pressure and hydrogen-ion concentration in the protoplasm, and for these latter functions the particular anions or cations present are of minor importance.

These considerations allow one to understand something about the total nutrient demands of the plant. Rapid growth can only take place when there is an adequate quantity of enzymes present, and hence after the plant has absorbed adequate quantities of the minerals necessary for their functioning. The maximum demand for these minerals therefore occurs when the plant is young, and the supply can be reduced later in the season; for as the cells in which the enzymes are situated age, much or all of these minerals can be transferred to new growing points to build new enzymes there. Further, if some of the minerals needed by the enzymes are in short supply, the older cells containing the enzyme may die prematurely and the limiting element transferred to the growing point. This need not affect the yield of cereals or root crops since it is food reserve material that is harvested, but it can severely limit the yield of pasture and forage crops which are grown for their green, and therefore actively functioning, leaves. Hence, these green crops must be able to obtain an adequate supply of all essential minerals throughout their growing season.

These points are illustrated in Fig. 1, taken from some work of A. E. V. Richardson and H. C. Trumble[1] on the uptake of nutrients, and the rate of growth of barley. Nitrogen, phosphate, potassium and calcium are all taken up rapidly when the plant is small, as measured by the amount of dry matter present, but the rate of uptake falls when the plant is making its dry matter rapidly. The uptake of minerals, however, may continue even if they are not needed by the plant, for plants take up minerals because they are present in the soil solution, and this uptake goes on all through the active life of the roots.

The concentration of cations in some plant tissues, such as the actively functioning leaves and the fruits, tends to be a characteristic of the crop and fairly independent of the soil and manuring. Thus D. J. Watson[2] quotes the results of leaf analyses made on the Rothamsted permanent mangold experiment for the six years 1878–83, which showed that the leaf contained between 300 and 360 milli-equivalents of cations (sodium, potassium, magnesium and calcium) per 100 gm. of dry matter when the manuring, and in consequence the actual composition of the

[1] *J. Dept. Agric. S. Aust.*, 1928, **32**, 224. [2] *Emp. J. Expt. Agric.* 1946, **14**, 57

bases present was varied within wide limits. D. R. Hoagland and J. C. Martin[1] found that tomato plants contained about 300 milli-equivalents of cations per 100 gm. of dry matter, although the potassium content could vary from 25 to 150 milli-equivalents. Similarly, T. B. van Itallie[2] found that Italian ryegrass contained about 200 milli-equivalents of cations per 100 gm. of dry matter in the leaf and F. E. Bear and A. L. Prince[3] found lucerne contained between 150 and 200 milli-equivalents.

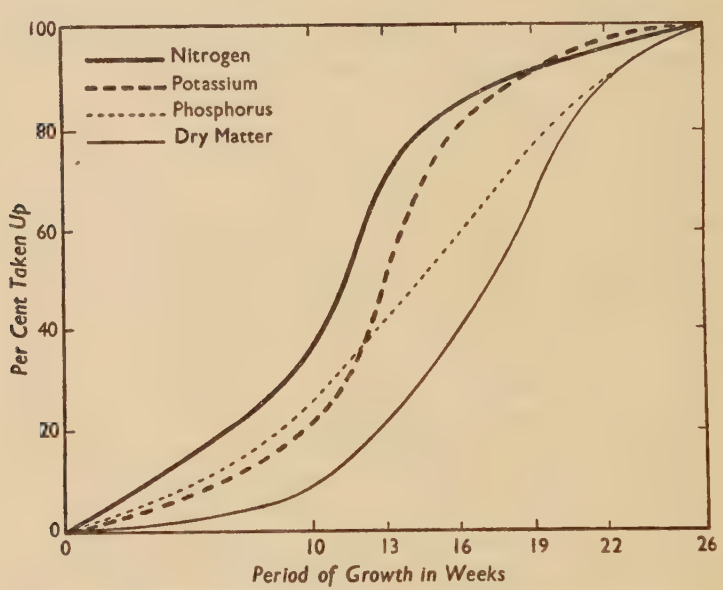


FIG. 1. Uptake of nutrients and production of dry matter in barley.

This constancy, however, is not exact. In the first place young tissues and leaves tend to have a higher ionic concentration in them than the older, and in the second place plants growing in a soil with an appreciable soluble salt content often accumulate considerable quantities of mineral salts in their tissues. As an extreme example some desert plants growing in saline soil can have between 20 and 50 per cent of their dry matter in the form of soluble salts, whereas most crops cannot accumulate more salts than 1–2 per cent of their dry matter.[4]

In some plants minerals that are no longer needed for metabolic processes are removed from the active tissues and often from the plant. One method is for the excess minerals to accumulate in mature leaves,

[1] *Soil Sci.*, 1933, **36**, 1. [2] *Soil Sci.* 1938, **46**, 175.
[3] *J. Amer. Soc. Agron.*, 1945, **37**, 217; 1948, **40**, 80.
[4] For examples of such plants, see M. M. Shukevich, *Trans. Dokuchaev Inst.*, 1939, **19**, No. 2, 39.

which then die. But there is also evidence that some of these minerals are excreted by the plant roots. Thus N. T. Deleano and his colleagues at Bucharest[1] have shown that the total amount of potassium in the aerial parts of cereals and tobacco decreases towards the end of their growing season, and this potassium is presumably excreted into the soil as it does not appear in the portion of the root system they were able to separate. Table 4 illustrates this effect for winter wheat growing on a heavy Essex clay,[2] though only the aerial part of these plants has been analysed. The table also shows, what was not illustrated in Fig. 1, that the silica content of the plant is almost directly proportional to the dry matter, and since towards the end of the season the dry matter is increasingly being formed in the grain, a portion of the plant low in silica, the silica content of the straw must be increasing during this period.

TABLE 4

Production of Dry Matter, and Assimilation of Nutrients from the Soil by Wheat growing in the Open Field

Weight in grams of substances in whole wheat plant grown in the field

	Before ear emergence			After ear emergence					
	1st Sampling (30.iv)	2nd Sampling (21.v)	3rd Sampling (4.vi)	4th Sampling (18.vi)	5th Sampling (2.vii)	6th Sampling (16.vii)	7th Sampling (23.vii)	8th Sampling (30.vii)	9th Sampling (6.viii)
Dry matter	770	2970	6190	9510	12270	14350	15060	14730	14210
Nitrogen	27	55	80	90	96	110	109	109	109
Potassium	26	79	140	149	121	103	94	86	75
Calcium	5·1	12·8	21·6	25·6	26·8	26·5	22·8	22·0	21·6
Phosphorus	3·2	10·5	18·0	24·4	24·8	27·0	27·8	27·8	27·8
Chlorine	6·0	15·1	24·2	28·8	33·9	30·5	27·4	23·6	19·3
Silicon	8	40	91	125	152	199	206	209	207

[1] *Biol. d. Pflanz.*, 1932, **19**, 249; 1933, **20**, 179; 1936, **24**, 19; also V. G. Bossie, *Dissert. d. Pharm. Fak. Bukarest*, 1934.

[2] F. Knowles and J. E. Watkins, *J. Agric. Sci.*, 1931, **21**, 612. For another example, see E. K. Woodford and A. G. McCalla, *Canad. J. Res.*, 1936, **14** C, 245.

CHAPTER III

THE INDIVIDUAL NUTRIENTS NEEDED BY PLANTS

In the following discussion a brief account will be given of the effects of the various nutrients on crop growth. It will usually be assumed that all nutrients are present in adequate supply except the one under discussion. The field symptoms of the various deficiencies will not be described, as full descriptions with coloured plates will be found in several standard works.[1] Nor is it relevant to the general purpose of this book to discuss in any detail the physiological functions of these nutrients in the plant.

NITROGEN

Nitrogen is essential for plant growth as it is a constituent of all proteins and hence of all protoplasm. It is generally taken up by plants either as ammonium or as nitrate ions, but the absorbed nitrate is rapidly reduced, probably to ammonium, through a molybdenum-containing enzyme. The ammonium ions and some of the carbohydrates synthesised in the leaves are converted into amino acids, mainly in the green leaf itself. Hence as the level of the nitrogen supply increases compared with other nutrients, the extra protein produced allows the plant leaves to grow larger and hence to have a larger surface available for photosynthesis, and in fact over a considerable range of nitrogen supply for many crops the amount of leaf area available for photosynthesis is roughly proportional to the amount of nitrogen supplied.

This effect of nitrogen in increasing leaf growth is not its only effect on the leaf, for the higher the nitrogen supply the more rapidly the synthesised carbohydrates are converted to proteins and to protoplasm and the smaller the proportion left available for cell wall material, which is mainly nitrogen-free carbohydrates such as calcium pectate, cellulosans, cellulose and low-nitrogen lignins.

This effect of nitrogen in increasing the proportion of protoplasm to cell wall material has several consequences. It increases the size of the cells and gives them a thinner wall, hence makes the leaves more succulent and less harsh. It also increases the proportion of water[2] and

[1] T. Wallace, *The Diagnosis of Mineral Deficiencies in Plants*, 1943, and Supplement, 1944, London, and *Hunger Signs in Crops*, ed. by G. Humbridge, Washington, 1941.

[2] For an example with mangolds at Rothamsted, see D. J. Watson, *Emp. J. Exp. Agric.*, 1946, **14**, 409.

decreases that of calcium[1] to dry matter: the former because protoplasm has more water and the latter because it has less calcium than cell wall material. Excessive amounts of nitrogen gives leaves with such large thin walled cells that they are readily attacked by insect and fungus pests and harmed by unfavourable weather such as droughts and frosts. A very low nitrogen supply on the other hand gives leaves with small cells and thick walls, and the leaves are in consequence harsh and fibrous. The nitrogen supply has one other noticeable effect on the leaf: it darkens the green colour. The leaves of plants growing with a low level of nitrogen compared with other nutrients are pale yellowish to reddish green, which darken rapidly as the nitrogen supply increases and become very dark green when it is excessive. Further increasing the nitrogen supply to the leaves tends to keep them green for a longer time, and in many cereals it increases the length of the growing season and delays the onset of maturity (see p. 33) presumably also through its effect in keeping the free carbohydrate content of the leaf low.

Crops grown for their carbohydrates, such as the root crops and the cereals, thus only benefit from nitrogen manuring through the increased leaf area brought about by the nitrogen, so that the additional yield of carbohydrate is usually less in proportion than the increase in leaf area. The root crops show this effect most strikingly when the length of the growing season is varied. Thus a high level of nitrogen manuring mainly affects the tops on a crop which is only in the ground for a short time, such as white turnips, but has a very considerable effect on both tops and roots on a crop that is in the ground for a long time, such as mangolds, as is shown in Table 5. Late sown sugar-beet also sometimes responds to nitrogen manuring by making a very large increase in leaf growth which is accompanied by a very disappointing yield of root.

The cereal crops of the temperate regions—wheat, barley, oats and rye—grown for grain and not for fodder, only require a moderate supply of nitrogen, for too high a level leads to excessive straw, as shown in Table 6 and in Plate I. These show the yield and the appearance of the wheat crop grown on Broadbalk at Rothamsted—a field that has been in wheat almost continuously since 1843, and the manuring of the plots has been continued unaltered for a long time. The plots shown in Plate I have been manured as follows: Plot 2, 14 tons per acre annually of farmyard manure and Plot 3 unmanured, both since 1843; Plots 5, 6, 7, 8 and 16 all have received annually 3½ cwt. of superphosphate, 200 lb. potassium sulphate, 100 lb. of magnesium sulphate and 100 lb. of sodium sulphate per acre since

[1] For a review of the literature, see K. C. Beeson, *Bot. Rev.*, 1946, **12**, 424.

TABLE 5

Relative Proportions of Roots and Leaves at Harvest under Nitrogenous manuring (Rothamsted)

Yields in tons per acre

Nitrogen in manuring lb. per acre	Rapidly growing crop: White turnips (1845–8)			Nitrogen in manuring lb. per acre	Slow growing crop[1]: Mangolds (1906–10)		
	Roots	Leaves	Roots / Leaves		Roots	Leaves	Roots / Leaves
None	8·20	2·70	3·04	None	5·29	1·14	4·64
47	9·90	4·30	2·30	86	17·91	3·80	4·72
137	10·25	6·15	1·67	184	29·32	6·20	4·73

1852 (Plot 16 since 1885) and annual dressings of ammonium sulphate or sodium nitrate to give 45, 90, 135 and 90 lb. per acre of nitrogen since these dates. The excessive development of straw on some of these plots induces a liability of the crop to lodge, and the very high nitrogen dressing on Plot 8 may delay the time the wheat comes to maturity.

TABLE 6

Effect of Increasing Nitrogen Supply on the Growth of Wheat, Rothamsted, 1852–64

Nitrogen in manure, lb. per acre	Yields in 1000 lb. per acre: Grain	Straw
None	1·06	1·86
43	1·68	3·03
86	2·18	4·28
129	2·27	4·78
172	2·29	5·22

In practice, however, these harmful secondary effects can be minimised by using suitable stiff short-strawed varieties, for, under most English conditions, the amount of nitrogen a crop will stand is determined by the onset of these secondary effects rather than by the extra yield of grain due to the high manuring ceasing to be economic. These harmful effects, in the case of the cereals, can also be minimised to some extent by applying the high level of nitrogen as late as possible to the crop, for D. J. Watson[2] found that delaying the time at which the nitrogen

[1] This table must be interpreted with some caution, for the relative weight of leaves at harvest on the different treatments may not accurately reflect their relative weights during the growing season.

[2] *J. Agric. Sci.*, 1936, **26**, 391.

top dressing was applied barely affected the increment in the grain yield due to the manure, but it appreciably reduced the increment in the straw yield.

The results given for the effect of nitrogen manuring on the cereals of the temperate region—that high nitrogen delays maturity of the crop and encourages growth of the straw relative to the grain—is not true for some tropical cereals such as maize and the sorghums, for with them a high level of nitrogen manuring has just the opposite effect: it hastens the time of flowering and maturity and increases the grain yield relative to the straw. This last point is illustrated in Table 7,

TABLE 7

The Effect of Increasing the Nitrogen Supply on the Yield of Maize, Rice and Wheat in the Nile Delta

(Abu Hammad, 1935 and 1936)

Yields of grain and straw in hundredweights per acre

Nitrogen supplied lb. per acre	Maize			Rice			Wheat		
	Grain	Straw	Grain / Straw	Grain	Straw	Grain / Straw	Grain	Straw	Grain / Straw
0	15·1	38·6	0·39	34·2	40·3	0·85	18·5	27·8	0·67
33	26·0	42·3	0·61	41·4	49·0	0·84	26·2	42·3	0·62
66	33·8	39·8	0·85	44·0	51·1	0·86	30·6	52·5	0·58
99	35·7	41·6	0·86						

derived from the results of some field experiments made on the same farm in the Nile Delta by F. Crowther and his associates.[1] The yield of maize grain can be more than doubled by the nitrogen without the yield of straw being appreciably affected, whereas the result with wheat is comparable with that obtained at Rothamsted and illustrated in Table 6. Rice is seen to be intermediate between these two, nitrogen manuring having almost no effect on the ratio of grain to straw. The sorghum dura in the Sudan Gezirah behaves like maize,[2] and other sorghums, the millets, cotton and sunflower have been stated to do likewise, whilst soybeans and buckwheat may behave like rice.[3]

The effect of nitrogen fertiliser on the nitrogen content of the crop depends both on the responsiveness of the crop and on the time the nitrogen is given relative to the development of the crop. If the nitrogen fertiliser greatly stimulates crop growth, the nitrogen content of the

[1] *Roy. Agric. Soc. Egypt, Bull.* 28, 1937.

[2] *Agriculture in the Sudan*, ed. J. D. Tothill, London, 1948, p. 474.

[3] M. H. Cailahjan, *C.R. Acad. Sci. U.S.S.R.*, 1945, **47**, 146. F. Crowther (*Roy. Agric. Soc. Egypt, Bull.* 31, 1937) showed that nitrogen manuring hastened the time of flowering of cotton.

fertilised crop, expressed as a percentage of its dry or fresh weight, will often decrease, although the total uptake of nitrogen per acre will increase, as is shown in Fig. 2.[1] This is because the extra dry matter which the added nitrogen stimulates the plant to produce has a lower nitrogen content than that produced by a nitrogen-starved plant. As the level of nitrogen supply increases, however, this stimulating effect grows smaller, so the uptake of nitrogen is increasing relative to the additional production of dry matter due to it: the nitrogen content of the dry matter in the crop now begins to rise. But this rise only becomes

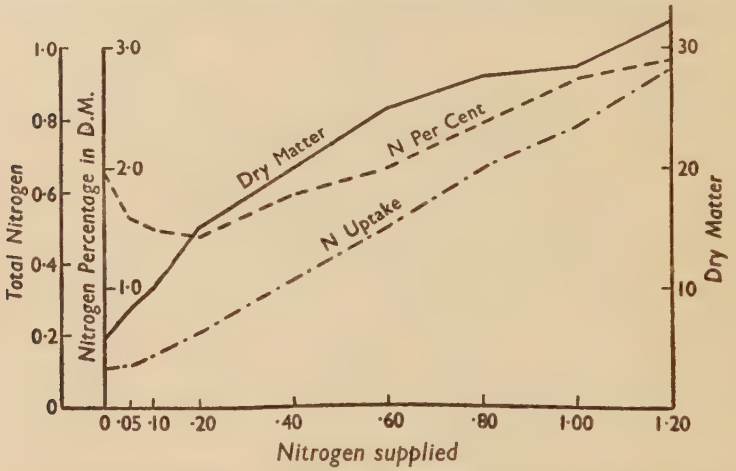


Fig. 2. The effect of increasing the nitrogen supply on the dry matter produced by mustard and on its nitrogen content.

appreciable when the growth of the crop ceases to respond economically to the additional fertiliser.

Nitrogenous fertilisers can often be made to increase the nitrogen content of the crop more economically if they are given sufficiently near harvest for the crop to absorb much of the added nitrogen, but for the synthesised proteins not to have time to increase the growth of the crop appreciably. Thus, by adding a nitrogen fertiliser to a meadow one to three weeks before it is cut, the protein content of the hay will be increased though the yield of hay will barely be affected.[2] During the war the Germans[3] also experimented with this method of converting nitrogen fertilisers into protein by applying them to cereal or potato

[1] For a field example with barley, see E. J. Russell, *Min. Agric., Bull.* 28, 2nd edn., 1933.

[2] H. B. Sprague and A. Hawkins, *New Jersey Agric. Expt. Sta., Bull.* 644, 1938; M. W. Evans, F. A. Welton and R. M. Salter, *Ohio Agric. Expt. Sta., Bull.* 603, 1939; A. H. Lewis, *J. Min. Agric.*, 1939, **46**, 77; *Emp. J. Expt. Agric.*, 1941, **9**, 43; W. S. Ferguson, *J. Agric. Sci.*, 1948, **38**, 33.

[3] See, for example, W. Selke, *Bodenk. PflErnähr.*, 1940, **20**, 1; 1942, **26**, 137, 151; 1943, **32**, 163.

crops at flowering time; they found nitrates were more efficient than ammonia, and that dressings of 40 lb. of nitrogen per acre, or 2 cwt. of nitrate of soda, gave substantial increases in the protein content of the crop.

The average response of crops to additional nitrogen under normal English agricultural conditions is shown in Table 8.[1] It shows that on the average 1 lb. of nitrogen, as sulphate of ammonia, gives about 1 lb. of protein and 10 to 15 lb. of starch equivalent.[2] These nitrogen responses differ from those to potash and phosphate in being relatively independent of climate if the rainfall lies between 22 to 40 inches, but they are reduced in years of considerable drought or excessive rain.

TABLE 8

Increase in the Amount of Crop and Food Value obtained by using 28 lb. of Nitrogen (1·2 cwt. of Sulphate of Ammonia) per acre

Average values for North European conditions

Crop	Crop cwt. per acre	Protein equivalent lb. per acre	Starch equivalent lb. per acre
Potatoes	17	16	360
Kale	35	52	360
Swedes	42	31	330
Mangolds	56	22	360
Sugar-beet roots	18	12 } 34	300 } 490
Sugar-beet tops	20	22 }	190 }
Cereal grain	4	31 } 37	300 } 400
Cereal straw	6	6 }	100 }
Meadow hay	6	31	210

Plants can take up their nitrogen either as ammonium or as nitrate ions, and most plants probably can use either equally easily. The main difference between these two ions is that all the nitrate in the soil is dissolved in the soil solution whilst, if the soil contains much clay or humus, much of the ammonium will be present as an exchangeable cation and hence not in solution. Perhaps for this reason a nitrate fertiliser is more rapid acting than an ammonium as it would be present in a higher ionic concentration round the plants' roots. But in most arable soils, added ammonium ions are rapidly oxidised to nitrate, so no matter what form of nitrogen is given, nitrate is the only form present in appreciable concentration in the soil solution for the plant

[1] Based on E. M. Crowther and F. Yates, *Emp. J. Expt. Agric.*, 1941, **9**, 77. For other British data, see D. J. Halliday, *Jealotts Hill Res. Sta., Bull.* 6, 1948.

[2] 100 lb. of nitrogen, the amount contained in 1,550 cubic feet of air—the volume of a fair-sized living-room—as sulphate of ammonia can provide enough additional food to feed one person for a year.

to take up. Concentrated organic nitrogen fertilisers, such as urea, dried blood, and hoof and horn must decompose to ammonia first, which is usually oxidised to nitrate as rapidly as it is formed.

Crops that respond to nitrogen manuring commonly take up and fix in their mature tissue between one-third and one-half of the nitrogen added as sulphate of ammonia, and a rather higher proportion of nitrogen added as nitrate; the remainder is lost to the crop and usually to the soil, probably being washed out into the subsoil during wet weather, though its fate has not been too well determined (see p. 295).

PHOSPHORUS

Phosphorus, as ortho-phosphate, plays a fundamental role in the very large number of enzymic reactions that depend on phosphorylation. Possibly for this reason it is a constituent of the cell nucleus and is essential for cell division and for the development of meristem tissue. Its concentration in these tissues can be demonstrated very beautifully if some radioactive phosphorus P^{32} is mixed with the main phosphorus nutrient supply. This radioactive phosphorus behaves exactly like ordinary phosphorus in the plant, except in so far as its radiations may harm the plant tissues if it is present in too high a concentration. These radiations however will affect a photographic plate so that this phosphorus can be made to register its position. A radio-autograph of the phosphorus in a young barley plant is reproduced in Plate II, and it shows very clearly that the actively growing meristematic leaf and root cells contain far more phosphorus, in fact between several hundred to several thousand times more, than the cells that have ceased to divide.[1]

Phosphate deficiency is very widespread in the world, and in many countries such as Australia and South Africa crop production is limited over enormous areas by phosphate supply. In the British Isles phosphate deficiency can be very marked on many of the Jurassic clays of the English midlands, on the acid Millstone grits of northern England and in large areas of Northern Ireland.[2] Further, in Great Britain crops are, on the whole, more responsive to phosphate fertilisers in the higher rainfall areas of the west than in the drier regions of the east;[3] though whether this is due to the crops having a higher phosphate demand in wet years, or whether this result is purely a reflection of the tendency for the soils in the moister regions to be more acid, and therefore stronger fixers of phosphate in an unavailable form (see p. 455), than those in the drier areas has not been determined.

[1] R. S. Russell and R. P. Martin, *Nature*, 1949, **163**, 71.

[2] For an excellent description of cases occurring here, see Scott Robertson, *J. Min. Agric. Northern Ireland*, 1927, **1**, 7.

[3] E. M. Crowther and F. Yates, *Emp. J. Expt. Agric.*, 1941, **9**, 77.

Phosphate deficiency differs from nitrogen deficiency in being extremely difficult to diagnose, and crops can be suffering from severe starvation without there being any obvious signs that lack of phosphate is the cause. By the time the deficiency has been recognised it may be too late to remedy it in annual crops. Thus wheat and barley take up much of their phosphate in the early stages of their growth, and starvation at this period cannot be rectified by a good supply later.[1]

Cereals suffering from phosphate starvation are retarded at every stage of their life-history, from the emergence of the second leaf to the time of ripening. They have a stunted root system and an even more stunted leaf and stem; the leaf colour is a dull greyish-green, a red pigment is often produced in the leaf bases and the dying leaves, and the tillering and the number of tillers bearing seed are depressed. On the other hand, except in extreme cases, the ratio of grain to straw is not affected. On soils badly deficient in phosphate, phosphatic fertilisers hasten the ripening processes, thus producing the same effect as a deficiency of water, but to a less extent. This ripening effect is well shown on the barley plots at Rothamsted: crops receiving phosphates are golden yellow in colour while those on the phosphate-starved plots are still green.

Certain indirect effects also follow: the ear of barley emerges from its ensheathing leaves a few days in advance of those receiving insufficient phosphate, and therefore has a better chance of escaping attack by the larvae of the gout fly (*Chlorops tæniopus* Meig.), which, hatching from their eggs on the top of the topmost leaf, crawl downwards seeking the ear for food.

Root crops suffering from severe phosphate shortage are also very stunted, and the effect of added phosphate can be spectacular. As a matter of history the early workers were so impressed with the great increase in the yield of roots obtained by phosphatic fertilisers that they assumed the phosphate had a specific action in encouraging root development, yet the permanent mangold field at Rothamsted (Barnfield) shows, in fact, that potassium increases the ratio of roots to tops far more than phosphate, and even the potassium effect is probably mainly a reflection of the early increase of leaf area.[2] Phosphate seems to increase leaf area without affecting the power of the leaves to transport carbohydrates to the roots, and it thus differs from nitrogen manuring, which also increases leaf growth but reduces their power of sending carbohydrates to the roots. Thus heavy nitrogen manuring of sugar-beet usually reduces the sugar content of the beet somewhat, although it may increase the amount of sugar produced per acre very

[1] W. F. Gericke, *Bot. Gaz.*, 1925, **80**, 410; W. E. Brenchley, *Ann. Bot.*, 1929, **43**, 89.
[2] D. J. Watson and E. J. Russell, *Emp. J. Expt. Agric.*, 1943, **11**, 49, 65.

considerably. All the experimental evidence available is in accord with this generalisation, and the statements made that crops respond especially well to dressings of phosphate on heavy soils is only a reflection of the low phosphate status of many English clay soils, and is not due to the power of phosphates to mitigate the effects of deficient aeration.

Excess of phosphate over the amount required by the crop sometimes depresses crop yield.[1] This usually occurs on light soils in dry years and has been attributed to the hastening of the maturation processes and consequent reduction of vegetative growth.

Plants take up their phosphorus almost exclusively as inorganic phosphate ions, probably only as $H_2PO_4^-$ ions,[2] and it is probably because of this that many plants suffer from phosphate deficiency in alkaline soils, for, as will be discussed on p. 451, the proportion of soluble phosphate ions in the $H_2PO_4^-$ form becomes very small if the *p*H rises above 8. Other phosphates besides orthophosphate act as phosphatic fertilisers, as for example meta- and pyro-phosphates, and though it has not yet been rigorously demonstrated it is probable that these anions are hydrolysed to the orthophosphate before being absorbed.[3] Plants are, however, relatively inefficient users of phosphates in the field, for rarely more than 20 to 30 per cent of the amount supplied as fertiliser is taken up.

SULPHUR

Sulphur is an essential constituent of many proteins and occurs also in the oils produced by certain plants such as the mustard oil of the Brassicae.

The best known deficiency disease due to lack of sulphur is tea yellows,[4] which occurs in parts of Nyasaland; but some of the most striking improvements in the yield of farm crops have been obtained with lucerne. There is a large region in the centre and west of the United States and extending into Canada, where yields of lucerne in particular, and other leguminous crops to a less extent, are limited by the amount of sulphates given in the fertiliser, and increases of yield ranging from 50 per cent to tenfold can be brought about by dressings of 2 to 4 cwt. of gypsum per acre.[5]

[1] For instances, see E. J. Russell, *J. Inst. Brew.*, 1923, **29**, 631 (barley); J. C. Wallace, *J. Min. Agric.*, 1926, **32**, 893; *Rothamsted Conf. Repts.*, No. 16, 1934 (potatoes).

[2] T. H. van den Honert, *Versl. Vergad. Vereen. Proefsta. Personeel.*, 1933, **13**, 7; *Natuurk. Tijdschr. v. Nederl. Ind.*, 1937, **97**, 150.

[3] W. T. McGeorge, *Arizona Agric. Exp. Sta., Tech. Bull.* 82, 1939.

[4] H. H. Storey and R. Leach, *Ann. Appl. Biol.*, 1933, **20**, 23.

[5] See, for example, F. J. Alway (Minnesota), *Proc. 1st Int. Congr. Soil Sci.*, Washington, 1927, **3**, 590; W. Crocker, *Soil Sci.*, 1945, **60**, 149; *Rept. Min. Agric. Dom. Canada*, 1945, 91. For the effect of sulphur on the growth of clover in Florida, see R. W. Bledsoe and R. E. Blaser, *J. Amer. Soc. Agron.*, 1947, **39**, 146.

POTASSIUM

Potassium is one of the essential elements in the nutrition of the plant, and one of the three that are commonly in sufficiently short supply in the soil to limit crop yield; hence it often needs to be added regularly in the fertiliser. Potassium differs from nitrogen and carbon, however, in not being a constituent of the plant fabric; it only appears to play a part in its metabolism. It seems to be important in the synthesis of amino acids and proteins from ammonium ions, for plants growing in solutions high in ammonium and low in potassium can have their tissues killed by the high concentration of the ammonium ions that accumulate in them under these conditions.[1] It is interesting to note that the only other element known that can replace potassium in this function is rubidium.[2] It is also probably important in the photosynthetic process, for potassium shortage in the leaf is commonly considered to lead to low rates of carbon dioxide assimilation,[3] though D. J. Watson[4] has been unable to confirm this on crops grown on the Rothamsted farm: it increased the leaf area and might put up the efficiency of assimilation slightly, but its effect was variable and always much smaller than that of nitrogen. But a discussion on the general effects of potassium deficiency is complicated by the fact that they depend so much on the relative concentration of other elements, particularly sodium and calcium in the plant tissues.[5]

In the field the potassium supply in the soil may be adequate for crops growing under conditions of a low nitrogen and phosphorus supply, but become inadequate if these are increased. Hence, signs of potassium starvation are often seen when only nitrogenous and phosphatic fertilisers are given to a crop; and the most characteristic sign is the premature death of the leaves.

When nitrogen and potassium are simultaneously in short supply, the plants are stunted, their leaves are small and rather ashy-grey in colour, dying prematurely, first at the tips and then along the outer edges, and the fruit and seed is small in quantity, size and weight. These effects are general, and are seen on all soils, but best on light sandy or chalky soils and on certain peaty soils; and it is on these soils that potassic fertilisers are most likely to act on all crops. With large supplies of nitrogen relative to potassium, on the other hand, the leaves are large but relatively inefficient photosynthesisers; hence an abnormal concentration of nitrogen compounds compared to carbohydrate occurs

[1] T. W. Turtschin, *Ztschr. Pflanz. Düng.*, 1934, A **34**, 343; M. E. Wall, *Soil Sci.*, 1940, **49**, 393.
[2] F. J. Richards, *Ann. Bot.*, 1941, **5**, 263, who used barley plants.
[3] F. G. Gregory with F. J. Richards, *Ann. Bot.*, 1929, **43**, 119; with E. C. D. Baptiste, ibid., 1936, **50**, 579; O. Eckstein, *Plant Physiol.*, 1939, **14**, 113.
[4] *Ann. Bot.*, 1947, **11**, 375.
[5] For a discussion of these effects, see F. G. Gregory, *Ann. Rev. Biochem.*, 1937, **6**, 557.

in the leaf, leading to various undesirable effects, such as the greater liability of these leaves to fungus and bacterial diseases, and to a reduced resistance against damage by drought compared with those receiving more adequate dressings of a potassium fertiliser. Thus potassium acts as a corrective to the harmful effects of nitrogen, and is therefore often required for crops receiving high levels of nitrogen manures.

An adequate supply of potassium in the leaf is probably essential for the photosynthetic process to go on efficiently, and results, such as those given in Table 9, have been used to demonstrate the truth of this statement. This table gives the weight of mangold tops and roots

TABLE 9

Action of Potassium Salts on the Yield of Mangolds

Barnfield, Rothamsted, 50 years, 1876–1928[1]

Yields in 1,000 lb. per acre

	Roots			Leaves		
Nitrogen supplied in manure, lb. per acre . . .	none	86	184	none	86	184
Series[2]	O	A	AC	O	A	AC
No potassium salts[3] . .	10·01	15·01	21·26	2·35	5·85	7·37
With potassium sulphate, 500 lb. per acre . .	9·03	30·24	50·51	2·08	6·29	11·65

at harvest obtained on certain plots at Rothamsted, some of which receive potassium, but all of which receive phosphate. It shows that with moderate dressings of nitrogen, given as sulphate of ammonia, potassium doubles the weight of roots, but has only a small effect on the yield of tops. One cannot argue, however, that this increase was necessarily due to the greater efficiency of the leaves, for D. J. Watson[4] has shown that the potassium increased the size of the leaves in the early part of the growing season, though this effect had disappeared by harvest, and that this initial increase was sufficient to account for the differences in the yield of roots without having to assume any effect of potassium on the efficiency of photosynthesis.

A result entirely similar to mangolds is found with sugar-beet. The

[1] Excluding 1885 when nitrogenous fertilisers were not applied owing to poverty of crop, and 1908 and 1927 when the crop failed.

[2] Series A as 400 lb. ammonium salts to 1915; 412 lb. sulphate of ammonia since. Series AC as Series A, but in addition 2,000 lb. rape cake.

[3] Series 5 and 6 respectively. Each receives 3½ cwt. per acre of superphosphate each year.

[4] *Ann. Bot.*, 1947, **11**, 375.

results of a large series of manurial experiments carried out over the sugar-beet areas of Great Britain are given in Table 10.[1]

TABLE 10

The Effect of Fertilisers on the Yield of Sugar-beet

Great Britain, 1934–48 (359 experiments)

	Mean yield	Response to		
		Sulphate of ammonia	Superphosphate	Muriate of potash
		4 cwt./acre	6 cwt./acre	2½ cwt./acre
Roots, tons per acre	11·2	1·2	0·4	0·5
Sugar, per cent	17·3	—0·4	0·0	0·2
Sugar, cwt. per acre	38·8	3·5	1·5	2·1
Tops, tons per acre	9·5	2·7	0·3	0·3

Nitrogen alone depresses the sugar content, potassium increases it and phosphate has no effect, though these experiments, like that in Barnfield, cannot furnish the information required for their correct physiological interpretation.

Crops differ greatly in their responsiveness to potassium. Many fruit trees—apples, gooseberries, red currants—need ample supplies of potassium for good cropping; beans and potatoes among British field crops, and tomatoes among the glasshouse crops, are all very responsive. Leguminous pasture plants—clovers and lucerne—also seem to need adequate supplies of potassium, particularly if they are to compete successfully with grasses;[2] and for lucerne in addition potassium increases its winter hardiness, possibly because it encourages the plant to store more carbohydrate and protein in its root system.[3]

Excess potassium in the soil, as brought about by too high a level of potassium manuring for example, will reduce very considerably the amount of other cations the crop can take up (see p. 66), and this may lead to crop growth being badly upset by these induced deficiencies of other cations.

CALCIUM

Calcium appears to be essential for the growth of meristems, and particularly for the proper growth and functioning of root tips. It is also present as calcium pectate, which is a constituent of the middle

[1] E. M. Crowther, *Roth. Expt. Sta. Rept.*, 1939–45, revised to include later data.

[2] For the Rothamsted experiments on this point, see J. B. Lawes and J. H. Gilbert, *Phil. Trans.*, 1900, **192** B, 156; W. E. Brenchley, *Manuring of Grassland for Hay*, London, 1924.

[3] L. F. Graber *et al.*, *Wisconsin Agric. Expt. Sta., Res. Bull.* 80, 1927.

lamellae of the cell walls, and possibly for this reason it tends to accumulate in the leaf.[1]

Calcium deficiency typically occurs on very acid soils, though the harmful effect of acid soils is often due to causes other than calcium deficiency; but it appears to occur also on some alkaline soils low in calcium but high in sodium. In general, however, farm crops are rarely limited by lack of calcium alone, though in this country during the war, cases of potatoes suffering from calcium deficiency were not uncommon on newly ploughed-up common or waste lands if the land had not previously been limed. The calcium status of acid soils undoubtedly is one of the factors that complicates the easy prediction from the *p*H of the soil alone whether a soil needs liming before a given crop can be grown on it.

Calcium deficiency appears to have two effects on the plant: it causes a stunting of the root system and it gives a fairly characteristic appearance to the leaf. Calcium deficiency also may have an indirect effect on the plant by allowing other substances to accumulate in the tissues so much that they may either lower the vigour or actually harm the plant. Thus a good calcium supply helps to neutralise the undesirable effects of an unbalanced distribution in the soil of nutrients and other compounds that can be taken up by the plant.

High levels of calcium in a soil, such as occur, for example, in some calcareous soils, have no direct harmful effect on most crops, but they may have several undesirable secondary effects. A high level depresses the uptake of magnesium and potassium; and in particular, calcareous soils typically require high levels of potassic fertilisers, a fact very well known on the thin chalk soils of southern and eastern England.

MAGNESIUM

Magnesium is needed by all green plants as it is a constituent of chlorophyll. It also seems to play an important role in the transport of phosphate in the plant, and possibly as a consequence of this it accumulates in the seeds of plants rich in oil, for the oil is also accompanied by an accumulation of lecithin, a phosphate containing fat.[2] Thus the phosphate content of a crop can sometimes be increased to a higher level by adding a magnesium rather than a phosphatic fertiliser, and it is for this reason that magnesium silicates, such as finely ground serpentine[3] or olivine,[4] are sometimes added to superphosphate to increase its effectiveness.

[1] For a review of the calcium nutrition of plants, see F. Kersting-Münster, *ForschDienst.* 1938, **5**, 48, and 8 papers in *Soil Sci.*, 1948, **65**, 1–128.

[2] For a recent symposium on the role of magnesium in plant nutrition, see *Soil Sci.*, 1947, **63**, 1–28.

[3] See, for example, H. O. Askew, *New Zealand J. Sci. Tech.*, 1942, **24** B, 79, 128.

[4] D. U. Druzhinin, *Ztschr. Pflanz. Düng.*, 1936, **45**, 303.

Magnesium deficiency often occurs on acid sandy soils that are also deficient in calcium, and it is then rectified by using a dolomitic instead of a purely calcareous limestone. But, as will be discussed on p. 66, it can also be induced by unbalanced manuring, such as by an excessive use of potassium fertilisers, particularly as the sulphate, or even by sodium chloride, and this is a common cause of the magnesium deficiency that can sometimes be seen on orchard trees, tomatoes, tobacco, cotton and sugar-beet. This induced deficiency is very dependent on season and does not always reduce the yield, but can be cured, if it is really necessary to use such large dressings of potassic or sodium fertilisers, by adding soluble magnesium salts to the soil or, better still, by spraying them on the crops.

SODIUM

Sodium does not seem to be an essential element for any crop, even for salt marsh plants, yet certain crops undoubtedly grow better in the presence of available sodium supplies than in their absence, the sodium in these cases appearing to carry out some of the functions that potassium usually fulfils. Crops can be divided into four groups with respect to their relative needs of sodium compared to potassium: some need sodium for optimum growth, some benefit if available sodium is present, some can tolerate part of their potassium supply being replaced by sodium and some can make no use of sodium even if the potassium supply is restricted. Table 11[1] shows the groups into which various agricultural crops are believed to fall, though the grouping may depend somewhat on climatic conditions.

TABLE 11

Effect of Sodium applied as a Nutrient on several Crops

Degree of benefit in deficiency of potassium		Degree of benefit in sufficiency of potassium	
1. None to very slight	2. Slight to medium	3. Slight to medium	4. Large
Buckwheat	Barley	Cabbage	Celery
Lettuce	Broccoli	Kale	Mangold
Maize	Brussels sprouts	Kohlrabi	Sugar-beet
Potato	Carrot	Mustard	Swiss chard
Rye	Cotton	Radish	Table beet
Soybean	Millet	Rape	Turnip
Spinach	Oat		
Strawberry	Pea		
Sunflowers	Tomato		
White bean	Wheat		

[1] Taken from P. M. Harmer and E. J. Benne, *Soil Sci.*, 1945, **60**, 137.

The role of sodium in the last group of plants is not known, though one of its effects is to increase the succulence of the plant, that is, the amount of water held by unit dry weight of leaf tissue. This may be the reason why it appears to increase the drought resistance of these plants. It also increases the leaf area of sugar-beet.[1] F. J. Richards[2] suggests another role of sodium in helping crops such as barley to grow in a potassium-deficient soil is that it prevents an accumulation of other cations that may be toxic to the plant, for a deficiency of one cation leads to an accumulation of others.

Sugar-beet and mangolds are probably the most sodium-demanding crops grown in western Europe, and although they need a reasonable potassium supply if they are to make proper growth, yet once this minimum supply has been provided, they require a good supply of sodium if they are to give satisfactory yields. Thus in a large series of manuring experiments on sugar-beet conducted throughout England during 1940–5,[3] the yield of sugar per acre was about 37 cwt. in the absence of potassium or sodium in the fertiliser used; it was increased by 2·8 cwt. an acre by 2 cwt. of muriate of potash, by 5·1 cwt. per acre by 5 cwt. of agricultural salt, and by 5·5 cwt. by the potash and salt together. Thus, here there is a definite need for sodium, and given the sodium there is no need for potassium; but in its absence potassium can in part take its place.

There is very little evidence that adding sodium salts to a soil increases the availability of the soil's potassium supply, nor in fact is there any theoretical reason to think that sodium ions are more powerful extractors of potassium from soils than are actively growing roots or root hairs.

SILICON

Great importance was attached by the older plant physiologists to silicon in the nutrition of the cereals and grasses, it being supposed to give strength to the straw.[4] Field experiments at Rothamsted disproved this view, neither barley straw nor grass being strengthened by manuring with sodium silicate. Certainly these crops contain much silicon in their dry matter, and, as can be seen from Table 4 on p. 29, the silicon content of wheat grown on a clay soil increases linearly with the dry matter. The function the silicon plays in these crops is not known, though F. Wagner[5] found crops grown without soluble silica were much more susceptible to mildew than those that had soluble silica available.

[1] J. J. Lehr, *Soil Sci.*, 1942, **53**, 399.
[2] *Ann. Rev. Biochem.*, 1944, **13**, 611.
[3] E. M. Crowther, *Brit. Sugar-Beet Rev.*, 1947, **16**, 19.
[4] For a recent review of this subject, see *Soils and Fert.*, 1946, **9**, 1; G. J. Raleigh, *Soil Sci.*, 1945, **60**, 133.
[5] *Phytopath. Ztschr.*, 1940, **12**, 427.

TABLE 12

Effect of Silicates on the Growth of Barley, 1864–1900. Rothamsted

	Yield of Dressed Grain, bushels		Yield of Straw, cwt.		Ratio $\frac{\text{Total Grain}}{\text{Straw}}$	
	Without Silicate	With Silicate	Without Silicate	With Silicate	Without Silicate	With Silicate
Nitrate only . . .	27·3	33·8	16·2	19·8	85·1	86·6
Nitrate + phosphate .	42·2	43·5	24·6	25·8	87·2	85·8
Nitrate + potassium salts	28·6	36·4	17·9	21·7	80·6	85·0
Nitrate + phosphate + potassium salts . .	41·2	44·5	25·3	27·6	82·7	82·1

Manuring the soil with sodium silicate can, however, increase crop yields on soils deficient in phosphate, as is shown in Table 12 for barley at Rothamsted. This result was later obtained for oats in water cultures by C. Kreuzhage and E. Wolff.[1] The phenomena were studied by A. D. Hall and C. G. T. Morison,[2] who concluded that silicates act by causing an increased assimilation of phosphoric acid by the plant, the seat of action being in the plant and not in the soil. O. Lemmermann[3] and R. A. Fisher[4], however, showed that the main effect of the silicate was to increase the amount of phosphate available in the soil, and that any other effect of silicate is of much less importance.

Great interest was taken in this problem, both in Germany and Japan, because it seemed at one time to open up both the possibility of replacing some of the imported phosphates by home-made silicates. So far the hopes have not materialised.[5]

CHLORIDES

Chlorides are taken up by most plants from the soil solution, and there is no evidence that any soils are so deficient in chlorides for crop failures to occur for lack of it, nor is there any evidence that crops would fail if chlorides were completely absent from the soil.

Some crops, however, often respond to additional dressings of chloride, for example, barley, lucerne and tobacco. Thus small

[1] *Landw. Vers.-Stat.*, 1884, **30**, 161–97.

[2] *Proc. Roy. Soc.*, 1906, **77** B, 455. See also W. E. Brenchley, E. J. Maskell and K. Warington, *Ann. Appl. Biol.*, 1927, **14**, 45–82.

[3] *Ztschr. Pflanz. Düng.*, 1929, A **13**, 28. This contains a critical review.

[4] *J. Agric. Sci.*, 1929, **19**, 132–9.

[5] For further information, see O. Lemmermann and H. Wiessmann, *Ztschr. Pflanz. Düng.*, 1922, A **1**, 185; D. S. Jennings, *Soil Sci.*, 1919, **7**, 210; Th. Pfeiffer, *Mitt. Deut. Landw. Gesell.*, 1923, p. 196; P. L. Gile and J. G. Smith, *J. Agric. Res.*, 1925, **31**, 247; W. Krüger and G. Wimmer, *Bied Zbl.*, 1928, **57**, 414; *Ztschr. für Zückerind.*, 1927, 127; H. Wiessmann, *Ztschr. Pflanz. Düng.*, 1925, A **4**, 73.

dressings of chlorides appear to increase the yield and improve the texture of the tobacco leaf without affecting its burning qualities, though larger dressings, which still increase the yield, lower this quality.[1]

There is no strong evidence that chloride has any specific effect on plant growth, though it may sometimes hasten maturity. Its main function, for which, however, it is not specific, is as an osmotic pressure regulator and a cation balancer in the cell sap and in the plant cells themselves.

In natural conditions plants receive measurable quantities of chlorides (chiefly sodium chloride) in the rain, and the amount is greater in the wetter western parts of the country than in the east. At Rothamsted the amount of chloride brought down averages 16 lb. per acre per annum and fluctuates between 10·3 and 24·4 lb.;[2] it comes chiefly in the winter months. But nearer the sea the amounts become very high, rising, according to N. H. J. Miller's determinations in rain-water from the Hebrides,[3] to:

	Annual rainfall in.	Chlorine per acre lb.
Laudale . .	76·89	168·5
Butt of Lewis[4] .	40·57	6884·0
Monarch . .	47·21	2723·0
Barrahead[5] .	33·93	5753·0

Trace Elements in Plant Nutrition

Plants need very small quantities of certain elements—the so-called trace or minor elements—for their nutrition, and these include iron, manganese, zinc, copper and boron, whilst molybdenum is beneficial under some circumstances. These elements are called trace elements, because only very small quantities, ranging from a few ounces to a few pounds per acre, are usually needed by the crop; and in fact C. S. Piper and A. Walkley[6] estimate that a full crop of oats only removes about ¼ oz. of copper, 1–2 oz. of zinc and 7 oz. of manganese, compared to 7 lb. of phosphorus per acre. But it must be realised that there is no sharp distinction between elements needed in large and small quantities, magnesium and sulphur being two good examples of intermediate elements for many crops. The literature on trace elements is now very

[1] *J. Amer. Soc. Agron.*, 1929, **21**, 113.
[2] E. J. Russell and E. H. Richards, *J. Agric. Sci.*, 1919, **9**, 309.
[3] *J. Scottish Met. Soc.*, 1913, **16**, 141–58. [4] Collected at 70 feet above sea-level.
[5] Collected at 620 feet above sea-level. [6] *Aust. J. Counc. Sci. Indust. Res.*, 1943, **16**, 217.

extensive, and the readers should refer to recent books and reviews[1] for more detailed discussion on their role in plant nutrition.

A shortage of one or more of these elements usually, but not always, affects the appearance of the plant, giving the leaves a chlorotic, bronzed or mottled colour, or altering their habit of growth, or causing the death of the growing points, so giving the plant a rosette appearance. Plants suffering from trace element deficiencies need not show any symptoms of the deficiency at all—except in so far as growth is not as good as it might be, or they may only display symptoms for a short period in the growing season. Sometimes the symptoms are sufficiently characteristic for the deficiency to be diagnosed visually,[2] but often they are so indefinite, or even suppressed altogether, that they can only be diagnosed by chemical tests, either by analysing the minerals in the leaf tissue or by applying small quantities of any element suspected of being deficient to selected leaves or shoots of the plant.

Deficiencies of the trace elements need not be made good by adding the deficient element to the soil: it is often more economical either to spray it on the leaves of the plant, or, if it is a tree, to insert pellets containing it under the bark in the trunk. Further trace element deficiencies often occur in soils which contain adequate quantities of the element, but in a form unavailable to the plant. Under these conditions the deficiency cannot usually be made good by adding some of the element to the soil. In general, increasing the acidity of the soil by any means, such as placement of sulphur near the plant for example, will increase the availability of all the trace elements except molybdenum. As a corollary, if an acid soil is suspected of having any trace element in minimal quantities, liming that soil may easily induce a deficiency of that element. Trace element deficiencies have the characteristic that their severity on a given soil depends very strongly on the season, hence the climate affects either the trace element requirements of the crop or else the availability of their compounds in the soil to the crop.

On many soils, plants suffer from a deficiency of a number of elements simultaneously, though they may only show the symptoms of one, or even of none of them. An observation of W. A. Roach[3] illustrates the complexities arising in such a soil. Potatoes growing on a marsh soil in Kent showed symptoms of manganese deficiency which

[1] See, for example, *Imp. Bur. of Soil Sci., Tech. Comm.* No. 39, 1940; W. E. Brenchley, *Bot. Rev.*, 1936, **2**, 173; *Biol. Rev.*, 1943, **18**, 159; a series of papers in *Soil Sci.*, 1945, **60**; W. Stiles, *Trace Elements in Plants and Animals*, Cambridge, 1946. There is the exhaustive *Bibliography on the Minor Elements* originally compiled by L. G. Willis and published by the Chilean Nitrate Education Bureau, New York, 3rd ed., 1939, and subsequent supplements.

[2] For colour reproductions of some of these symptoms, see *Hunger Signs in Crops*, ed. G. Hambridge, Washington, 1941; T. Wallace, *The Diagnosis of Mineral Deficiencies in Plants*, London, 1943, and a *Supplement*, 1944.

[3] *E. Malling Res. Sta. Ann. Rept.*, 1945, pp. 29, 83.

were cured by spraying with manganese, though this did not affect the yield of the crop. The crop was, however, also suffering from zinc deficiency although no symptoms whatever of this were visible; spraying with zinc improved the yield slightly, but spraying with zinc and manganese gave a very considerable increase in yield and obviously rectified the main cause of the low yields. Roach considers that the yields of many of our orchards are unnecessarily low because of a combined deficiency of several of these elements, none of which is severe enough to cause any visible symptoms. Again, plants can have their vitality lowered by shortages of trace elements without any symptoms of deficiency showing.

Trace elements have another characteristic; namely, that they are normally all very poisonous if present in the soil in an available form in more than very small amounts. Hence, it is very dangerous to apply them indiscriminately at more than very light dressings; though if concealed trace element deficiencies are found to be widespread it will obviously become important to discover just how high a concentration of a mixture of them can be applied indiscriminately without harming the crop.

IRON

Iron deficiency typically shows up as a chlorosis, particularly on calcareous soils, but not all calcareous soils induce iron chlorosis, and crops differ markedly in their susceptibility to this trouble. Fruit trees and bushes are the crops of most economic importance to be affected in England; but the calcifuge leguminous plants, such as yellow and blue lupins and serradella, as well as many conifers, are also strongly affected. Iron deficiency chlorosis can also be induced as a result of potassium deficiency, and by over-manuring with phosphates on neutral or calcareous soils; it also occurs on soils high in available zinc and under some conditions high in available manganese and copper.[1]

Lime-induced chlorosis is the commonest of the iron deficiency chloroses, and it is also one of the most difficult deficiencies to cure. It is probable that the trouble lies both in the inability of the plant to extract sufficient iron from the soil and also in an appreciable proportion of the absorbed iron being in combinations unavailable to the plant cells for their metabolism; for chlorotic leaves do not necessarily have a low total iron content though they have a low soluble iron content. The chemical characteristic of these leaves is that they have a very high potassium and a rather low calcium content, and, in fact, young, chlorotic leaves may cause such a drain on the potassium supplies

[1] For a recent review of this subject, see T. Wallace and E. J. Hewitt, *J. Pomol.*, 1946, **22**, 153; H. D. Chapman, *Ann. Rev. Biochem.*, 1945, **14**, 709.

Plot	2	3	5	6	7	8	16
Annual manuring	FYM	No manure	PK	PK 45 lb. N	PK 90 lb. N	PK 135 lb. N	PK 90 lb. N

N given as ammonium sulphate on plots 6, 7, 8 and sodium nitrate on plot 16

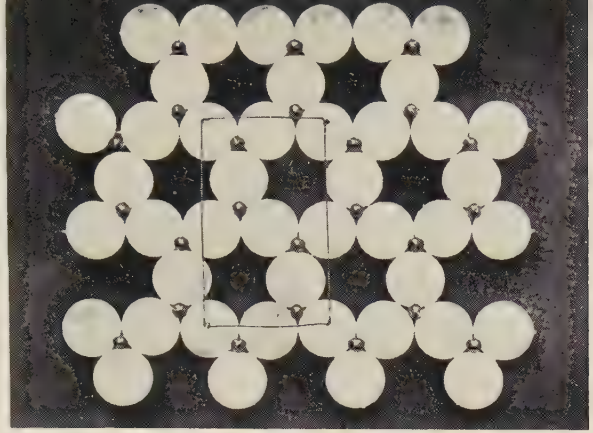
The effect of nitrogen fertilisers on the yield of wheat on Broadbalk in 1943

(*p. 31*)

Auto-radiographs of barley plants containing radioactive phosphorus

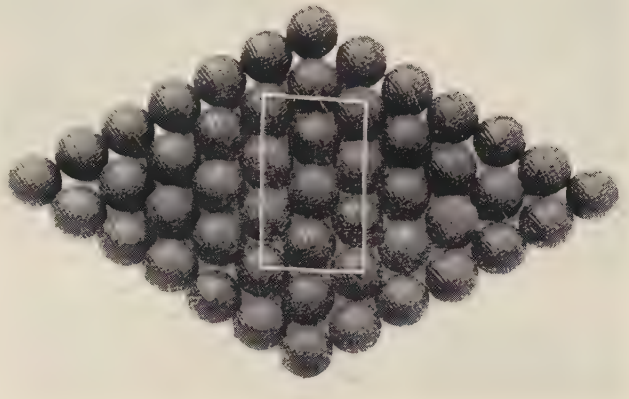
(*Left*) Showing the concentration of phosphorus in the tips of the growing roots (natural size)
(*Right*) Showing the concentration of phosphorus in the apical meristem (*a*) the leaf primordia; (*b*) the bases of leaf sheaves; (c) and (*d*) the initial of adventitious shoots (×53)

(*p. 36*)



The oxygen layer containing silicon in 4-co-ordination

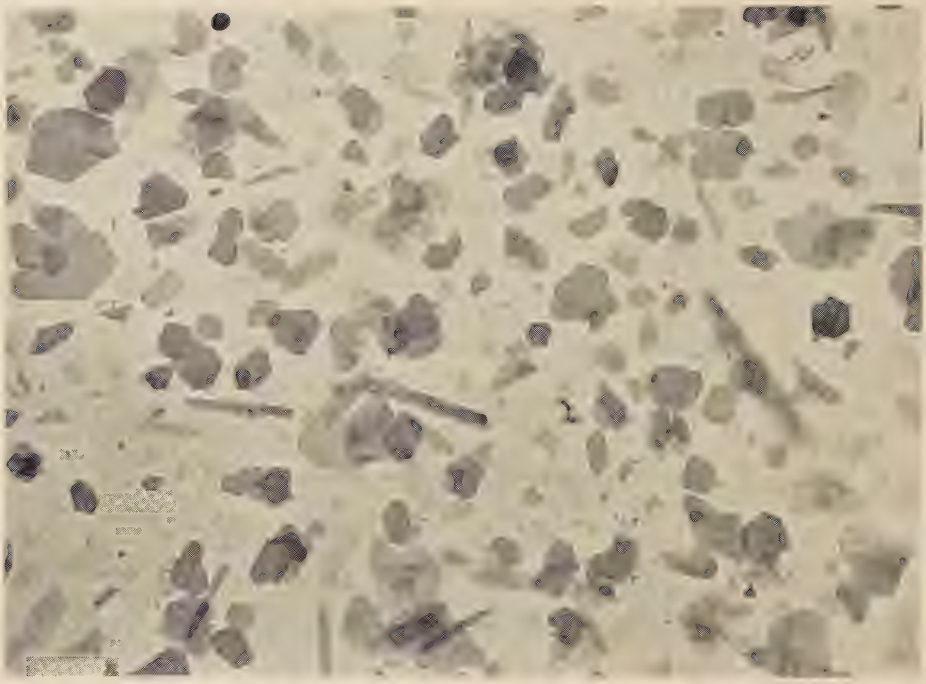
The oxygen and hydroxyl layer containing aluminium in 6-co-ordination



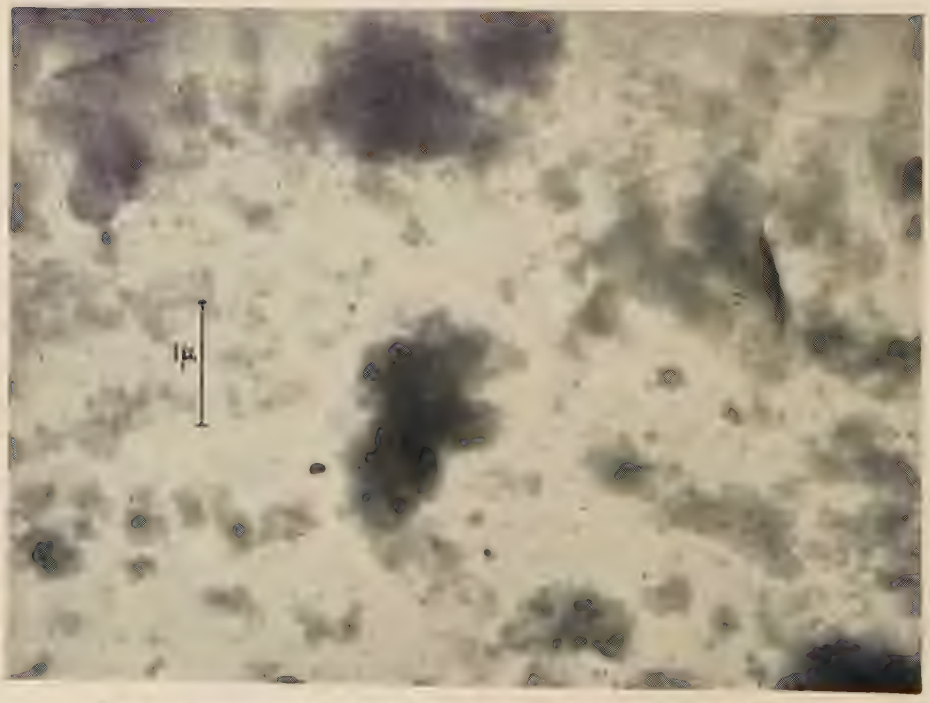
The hydroxyl layer in close packing

The arrangement of the layers to form a sheet of the mineral pyrophyllite

(*pp. 82–83*)



Electron microscope photograph of kaolinite particles between 0·1 and 0·2 μ (x 15,000)



Electron microscope photograph of bentonite particles (x 16,000)

These particles are too small and too thin to be resolved, and are mainly aggregated together in the photograph

(*p. 89*)

in the plant that the older leaves will suffer from potassium deficiency as a result. This chlorosis cannot yet always be controlled in practice. Farmyard manure and composts can sometimes be used to carry iron in a form available to the plant, but resistant to immobilisation in the soil; grassing down the land between orchard trees and mowing it regularly, leaving the mown grass on the ground, sometimes cures it, but is a method that is not always applicable: spraying with iron sulphate or inserting pellets of iron citrate or tartrate may also help. This trouble can possibly also be cured by adding to the soil some suitable iron silicates which appear to be able to supply iron to trees even in calcareous soils.[1]

Iron deficiency can be induced if a crop is growing on a soil containing too high a concentration of many metallic ions. Thus cobalt, copper, chromate, zinc, manganese and lead can all cause plants to show symptoms of iron deficiency as well as those of specific toxicity of these ions.[2] The trouble is sometimes due to an immobilisation of iron within the leaves themselves, for the plant leaves have a very high iron content, yet the trouble can be cured by repeatedly spraying the crop with iron sulphate. Thus, this trouble occurs on some of the zinc-rich soils derived from the dolomitic limestone in the Mendips,[3] and also can be caused by the use of industrial sewage sludges high in zinc, and can sometimes be cured by liming, though this, in turn, may induce manganese deficiency.

MANGANESE

Manganese deficiency typically occurs on calcareous or newly limed peats, particularly if the water table is high, though it can also occur on some neutral sandy soils and light loams. It can be easily induced by over-liming sandy podzolic and garden soils rich in organic matter. It rarely if ever occurs on acid soils. Many crops are susceptible: oats in particular among the cereals, potatoes, peas and to a less extent beans, sugar-beet and related crops, and many fruit crops and tung trees. Oats suffer from grey-speck disease, sugar-beet from a yellows, and peas from marsh spot.

Manganese deficiency occurs in crops growing on soils that contain adequate quantities of manganese for the crop, but in which the manganese is present in a form unavailable to it. Unfortunately the factors controlling the availability of the soil's manganese are not fully understood. Probably only divalent manganese is available to the plant, but this merely puts the question back to the soil factors that control the

[1] A. Demolon and E. Bastisse, *C.R. Acad. Agric.*, 1944, **30**, 501; E. Bastisse, *Ann. Agron.*, 1946, **16**, 434.
[2] E. J. Hewitt, *Nature*, 1948, **161**, 489; *Long Ashton Ann. Rep.*, 1948, 66.
[3] T. Wallace and E. J. Hewitt, *J. Pomol.*, 1946, **22**, 153.

proportion of manganese present in the divalent form, a question which is discussed on p. 465.

The main factor so far recognised that controls the availability of manganese in the soil is the *p*H. The more acid the soil the greater is the availability of the manganese,[1] and indeed the first harmful effect of too low a soil *p*H on some crops is the toxic effect of the large amount of manganese the plant takes up[2] (see p. 474). In this respect it differs from the other trace elements, for it is the only one that can accumulate in plant tissues in quantities far higher than are necessary for optimum growth. Hence, one method of reducing manganese deficiency in a soil is to make the soil more acid, as, for example, by the use of sulphur, or under some conditions of large quantities of ammonium sulphate.[3] It is also possible that a second cause of manganese deficiency may be that some soil bacteria, or some bacteria on the plant roots, oxidise the divalent manganese in the root zone of the crop.[4]

Manganese has several functions in the plant. It is a constituent of some respiratory enzymes, probably sometimes in association with iron, and of some enzymes responsible for protein synthesis. A good manganese supply may also sometimes help counteract the effect of poor aeration. Thus under conditions of poor aeration and low manganese, nitrates are a better source of nitrogen than ammonium ions, as the oxygen in the nitrate can act as a hydrogen acceptor in the respiration processes of the cells. But D. I. Arnon[5] showed that increasing the manganese supply to the root under these conditions had a much larger effect in increasing the growth of the plant (which was barley in his experiments) when ammonium rather than nitrate ions were the source of nitrogen. Manganese may also be concerned with the nitrogen metabolism of the plant. Thus S. G. Heintze[6] found that on fields where the levels of the different forms of soil manganese were fairly uniform, plants developed manganese deficiency symptoms most strongly on those parts of the field where the available nitrogen (actually the nitrifiable nitrogen, see p. 468) was highest, and this was not due to any extra growth the higher level of available nitrogen caused. On the other hand, plants suffering from manganese deficiency appear to have a higher concentration of nitrates and of most plant amino acids than normal plants, which suggests that manganese plays some role either in the synthesis of a particular amino acid, or of proteins from amino acids.[7]

[1] See, for example, H. J. Snider, *Soil Sci.*, 1943, **56**, 187.
[2] M. J. Funchess, *Alabama Agric. Exp. Sta., Bull.* 201, 1918; H. G. M. Jacobson and T. R. Swanbank, *J. Amer. Soc. Agron.*, 1932, **24**, 237; T. Wallace *et al.*, *Nature*, 1945, **156**, 778; J. B. Hale and S. G. Heintze, ibid., 1946, **157**, 554.
[3] D. W. Goodall, *J. Pomol.*, 1943, **20**, 136, for apple trees.
[4] F. C. Gerretsen, *Ann. Bot.*, 1937, **1**, 207.
[5] *Soil Sci.*, 1937, **44**, 91.
[6] *J. Agric. Sci.*, 1946, **36**, 227.
[7] E. J. Hewitt *et al.*, *Nature*, 1949, **163**, 681.

The dressings of manganese required to effect control of these deficiency diseases depends on the method of control practised. Manganese deficiency induced by over-liming can often be cured by spraying as little as 1–2 lb. per acre of manganese sulphate, but rates of 5–20 lb. per acre are commoner for sprays; and up to 40–50 lb. per acre for incorporation in peat soils.

ZINC

Zinc deficiency diseases are of great importance on many orchard soils in the U.S.A.; citrus, deciduous fruits, pecans and tung plantations all suffer in several areas, and in Florida maize and perhaps other crops in addition. Zinc deficiency diseases typically show up in climates having bright sunlight, are usually restricted to heavy soils or to sandy soils containing peat, and are most pronounced in slightly acid or neutral soils. Zinc deficiency has not been considered of any economic importance in European crops, because zinc deficiency symptoms have not been recognised here. But W. A. Roach's observations,[1] already quoted, on the response of many crops on some marshland soils of Kent which show no visible signs of zinc deficiency to additions of zinc, suggests that its importance here may have been under-estimated.

Plants differ markedly in their power of extracting zinc from the soil. On the zinc-deficient soils of Florida native weeds seem to be far better collectors of zinc than planted crops: L. H. Rogers, O. E. Gall and R. M. Barnett[2] found that native weeds growing on fallow land contained on the average 140 p.p.m. of zinc in their dry matter whilst a cover crop of crotalaria only contained 4–11 p.p.m., and they suggested that the best way of preparing the land for maize is to allow these native weeds to cover the land and then plough them in before the maize is sown. In the same way lucerne, which appears to be a strong extractor of zinc, is a valuable cover crop in orchards suffering from zinc deficiency, whenever it can be grown without competing with the trees for water or other nutrients.

The power of a plant to extract zinc from the soil also depends on the extensiveness of its root system. Thus zinc deficiency can occur in citrus trees growing on some heavy soils because the trees cannot form an extensive enough root system to tap a sufficiently large volume of soil from which to extract their zinc. It can be cured in these cases by growing crops that are efficient extractors of zinc and ploughing them in as green manures.

There is some evidence[3] that zinc deficiency can sometimes be caused by the soil micro-organisms competing with the plants for the small quantities of available zinc present.

[1] *E. Malling Res. Sta. Ann. Rept.*, 1945, pp. 29, 83.
[2] *Soil Sci.*, 1939, **47**, 237.
[3] W. H. Chandler, *Bot. Gaz.*, 1937, **98**, 625.

COPPER

Copper deficiency typically occurs in crops growing on newly reclaimed peats in Europe and the eastern States of the U.S.A., causing the so-called Reclamation Diseases.[1] But it has also been found on some sandy and gravelly soils in Australia and South Africa.

Copper appears to have two quite separate functions: one directly concerned with plant nutrition and one with the condition of the soil. One function of copper as a nutrient is to be present in the oxidation-reduction enzyme polyphenol oxidase. This enzyme is localised in the chloroplasts of the leaves in some plants such as spinach, hence may play a role in the photosynthetic process,[2] but it is also present in potato tubers where it is a respiratory enzyme. It is not known if copper has any other function in the plant, but there may be plants that need copper but do not contain this enzyme, though this point has not yet been critically established.

The function of copper in neutralising a harmful condition in the soil can be surmised from the fact that the quantity of copper sulphate that must be added to a soil to get maximum crop yield varies a hundredfold. Thus 250 lb. per acre of copper sulphate are commonly used in the Floridan Everglades,[3] about 50 lb. on some European and 10 lb. on some Michigan peats,[4] about 25 lb. on some calcareous sandy soils in South Australia[5] that apparently contain ample copper but in an unavailable form, and lowest of all, $2\frac{1}{2}$ lb. per acre is the recommended dressing, and 10 lb. is harmful, on some sandy soils in Western Australia.[6] W. S. Smith[7] suggested that the role of copper in the copper-deficient peats was to precipitate or inactivate certain toxins present in the peat, which he believed he had isolated.

In soils where the role of copper appears to be mainly as a nutrient, i.e. where low dressings only are required, it is possible that there is an interaction between the need for zinc and for copper, in the sense that crops may respond to zinc if copper is also given, but not if it is withheld.[8] Also, in these same conditions it is possible that copper responses are larger in hot, dry summers than in cool, moist ones.[9]

[1] For an account of these diseases and their cure in Holland, see W. J. Melchers and H. J. Gerritsen, *Koper als Onmisbaar Element voor Plant en Dier*, Wageningen, 1944.
[2] D. I. Arnon, *Plant Physiol.*, 1949, **24**, 1.
[3] O. C. Bryan, *J. Amer. Soc. Agron.*, 1929, **21**, 923.
[4] R. E. Lucas, *Proc. Soil Sci. Soc. Amer.*, 1946, **10**, 269.
[5] D. S. Riceman and C. M. Donald, *J. Dept. Agric. S. Aust.*, 1939, **42**, 959.
[6] A. S. Wild and L. J. H. Teakle, *J. Dept. Agric. W. Aust.*, 1942, **19**, ser. 2, 71, 242.
[7] *Diss.*, Wageningen, 1927.
[8] For Michigan peat soils, see R. E. Lucas, *Proc. Soil Sci. Soc. Amer.*, 1946, **10**, 269.
[9] Again for Michigan peats, see P. M. Harmer, *Proc. Soil Sci. Soc. Amer.*, 1946, **10**, 284. He also gives a list of the responsiveness of different crops to copper shortage.

MOLYBDENUM

Molybdenum is another element recently recognised as needed for the growth of some plants in the field, but it differs from the other elements so far mentioned in that plants can probably be grown perfectly satisfactorily without it, provided their nitrogen supply is present as ammonium ions. Plants grown without a molybdenum supply in the presence of nitrates accumulate nitrates in their tissues and the molybdenum is apparently essential for the nitrate-reducing enzyme.[1] Again leguminous plants are unable to fix nitrogen in the absence of an adequate molybdenum supply, and in fact every nitrogen-fixing organism so far recognised requires molybdenum for this process. It is not yet known if these two enzymes are the same, but if they are, it would suggest that the initial product of nitrogen fixation is a compound of oxygen and nitrogen rather than of hydrogen and nitrogen.

Molybdenum deficiency in the field was first recognised in Australia,[2] New Zealand and Tasmania,[3] and the crops first proved to need molybdenum were the clovers. Leguminous plants could only be grown on some of these acid sandy soils if they were given a dressing of between $\frac{1}{2}$ and 2 lb. per acre of either ammonium or sodium molybdate; and cases have been reported of clovers responding to similar dressings of molybdenum in Europe.[4]

Molybdenum deficiency has also been recognised in the field on non-leguminous crops such as perennial rye-grass in Tasmania[5] and cauliflower in New Zealand.[6] The deformity produced in cauliflower is similar to that known as "whiptail" which is found in some of the cauliflower growing districts in England, so that it is possible that this deficiency may also occur here.[7] Molybdenum deficiency has also been produced in a number of other crops, such as tomatoes[8] and lettuce[9] by growing them in water on sand cultures, but none of the laboratory examples so far found are inconsistent with the assumption that the sole function of the molybdenum is concerned with nitrate utilisation in the plant.

BORON

Boron would appear to be essential for all plants in greater or less

[1] See, for example, E. G. Mulder, *Plant and Soil*, 1948, **1**, 94; E. J. Hewitt *et al.*, *Nature*, 1949, **163**, 681.
[2] A. J. Anderson, *J. Aust. Inst. Agric. Sci.*, 1942, **8**, 73.
[3] E. F. Fricke, *Tasm. J. Agric.*, 1943, **14**, 69; 1944, **15**, 65; 1945, **16**, 1.
[4] H. Bortels, *Arch. Mikrobiol.*, 1937, **8**, 13; K. A. Dmitriev, *Khim. Sotsial. Zemled.*, 1938, No. 10, 80.
[5] C. G. Stephens and A. C. Oertel, *Aust. J. Counc. Sci. Industr. Res.*, 1943, **16**, 69.
[6] E. B. Davies, *Nature*, 1945, **156**, 392.
[7] E. J. Hewitt *et al.*, *Long Ashton Ann. Rep.*, 1947, 70.
[8] D. I. Arnon and P. R. Stout, *Plant Physiol.* 1939, **14**, 599.
[9] K. Warington, *Ann. Appl. Biol.*, 1946, **33**, 249.

degree. A shortage of boron typically affects the meristem or actively dividing tissues, so that characteristic symptoms of boron deficiency are death of the growing points of shoot and root, failure of flower buds to develop, disintegration of the vascular tissue and breaking down and blackening of the softer tissues. In the field, deficiency is shown in various ways, as in the heart rot of sugar-beet, "raan" of swedes, cracked stem in celery and browning in cauliflower. Boron deficiency does not necessarily indicate an actual shortage of boron in the soil; it may be present yet unavailable to the plant. It can be induced by over-liming, and it also shows up more strongly in dry than in wet seasons. The condition can be remedied by the addition of 10–12 lb. per acre of borax to the soil, heavier dressings usually being harmful unless the soil has been over-limed. It cannot be rectified by spraying a soluble borate on to the plant.

The primary role of boron appears to be concerned both with the uptake of calcium by the roots and with its efficient use in the plant, and sometimes the one and sometimes the other process first limits growth at low boron concentrations.[1] This was first demonstrated by W. E. Brenchley and K. Warington[2] for broad beans (*Vicia faba*), and has been confirmed for a number of other crops. It also appears to have a secondary role in broad beans, in which plant it was first recognised as an essential nutrient by Warington,[3] for an adequate boron supply is essential for the vascular system in the root to throw off branches to supply the nodule bacteria with carbohydrate,[4] so preventing them from becoming parasitic.

The importance of boron for plant development is sufficiently well recognised to make it a usual practice in some places to incorporate a small amount of borax with the fertilisers for sugar-beet, tobacco, turnips and doubtless other crops also. J. J. Lehr[5] has outlined the boron relations in plants and soil in a thesis drawing special attention to its importance for brassica crops, tomato and maize, and has also indicated the possible lowering of the boron status of many soils owing to the increasing difficulty of obtaining organic fertilisers, the greater purity of many of the inorganic fertilisers, and the frequent substitution of sulphate of ammonia for Chilean nitrate, which has a high boron content.

The supply of available boron can be readily washed out of soils, hence boron deficiency is typically found on highly leached soils. On the other hand, marine sediments are usually well supplied with it.

[1] For a recent symposium on this, see *Soil Sci.*, 1944, **57**.
[2] *Ann. Bot.*, 1927, **41**, 167; 1934, **48**, 743.
[3] *Ann. Bot.*, 1923, **37**, 629.
[4] W. E. Brenchley and H. G. Thornton, *Proc. Roy. Soc.*, 1925, **98** B, 373.
[5] Thesis. *De Betekenis van borium voor de plant*, Utrecht, 1940.

Boron, like most other minor elements, should be supplied to the soil in small frequent dressings, to minimise any risk of the toxic effects of too high a concentration.

Trace Elements in Animal Nutrition

Animals have not quite the same trace element needs as plants.[1] Thus all animals require iodine, though iodine deficiency diseases have rarely been reported among livestock. They need iron, manganese, copper and zinc, as do plants, but do not seem to require boron. Cattle and sheep, however, need cobalt, an element not apparently required by plants. Normally, if pastures cannot adequately supply the trace element needs of the grazing animals, these can be met either by giving the animals licks or drenches containing the missing trace element, or by mixing these in with the main fertilisers, usually with the superphosphate given to the pastures.

The difference between the trace element requirements of plants and animals can be seen in the effects of different hill grazings on the thriftiness of the sheep they carry. Thus, it is probable that sheep do better on some of the heather grazings than on the improved leys because the heather herbage is richer in trace elements.[2] The substitution of improved leys for the unimproved heather may require either the sheep or the land being given additional amounts of the more important trace elements, if any benefit is to be reaped from the increased amount of herbage produced.

The two main trace element deficiency diseases in animals are due to copper and cobalt. Copper deficiency can occur in cattle grazing on copper-deficient pastures; but it can apparently also occur on pastures adequately supplied with copper if the herbage contains at the same time sufficiently high concentrations of some other trace elements which can cause the copper to become unavailable. Thus swayback in sheep appears to be a lead-induced copper deficiency and teartness in pastures a molybdenum-induced copper deficiency, for the pastures giving these troubles have a herbage abnormally rich in lead and molybdenum respectively, and the troubles can at least be ameliorated by feeding the animals extra copper.

Cobalt is apparently needed by cattle and sheep to help with the fermentation of food in the rumen, for R. A. McCance and E. W. Widdowson quote a finding of C. J. Martin that the cobalt must be given by the mouth—it is no use injecting it into their bodies. Many poor pastures all over the world are now known to have too low a

[1] For a recent review, see F. C. Russell, *Imp. Bur. Anim. Nutr., Tech. Comm.* 15, 1944.
[2] B. Thomas *et al.*, *Emp. J. Expt. Agric.*, 1945, **13**, 93.

cobalt content for sheep or cattle to thrive on them. In Great Britain these are mainly found on some hill pastures, and the sheep suffer from a disease known as pine. Dressings of ½ to 2 lb. per acre of a cobalt salt are applied to the pastures and the effect lasts about three years. In New Zealand, where the soils are very deficient in phosphate also, it is usually applied mixed with superphosphate.

Animals can suffer from other deficiency diseases besides those due to trace elements. Thus, in parts of South Africa the herbage has such a low content of phosphate that the animals grazing on it suffer from acute phosphate starvation (see p. 436). Again, sheep need a fairly high content of available sulphur in their herbage to produce wool, as wool contains a high proportion of cystine, a sulphur-containing amino acid. The spring flush of good pastures on soils low in available sulphur can give a fodder too low in sulphur for the sheep, with a consequence that the quality of the wool falls—the wool becomes brittle and breaks easily.

Pasture plants can, however, contain sufficiently high concentrations of some elements in their tissues to be definitely harmful to animals feeding on them. The best known example is probably selenium in the United States. Prairie and range plants growing on seleniferous soils are not affected by the selenium, and some species can accumulate very large amounts; but animals feeding on these prairies may suffer severe selenium poisoning. Similarly, pasture grasses and clovers on some of the heavy Lower Lias clays of southern England may accumulate concentrations of molybdenum[1] that can seriously harm calves and young cattle grazing them. These are the teart pastures already mentioned in the paragraph dealing with copper-deficiency diseases.

The relation between the minerals composing the soil and the health of livestock grazing on the pasture or range can thus be very close. Thus the cobalt content of a rock tends to follow the magnesium content —their ions are of a similar size, hence hill grazings on granitic rocks, low in magnesium, tend to induce pine in sheep, whilst those on rocks well supplied with serpentine will be healthy.[2] Again, since some plants are much better extractors of these elements than others, the botanical composition of the herbage,[3] and because of this the way the grazing is managed, can affect the health of the stock markedly.

[1] W. S. Ferguson, A. H. Lewis and S. J. Watson, *J. Agric. Sci.*, 1943, **33**, 44.

[2] For examples, see E. B. Kidson, *J. Soc. Chem. Indust.*, 1938, **57**, 95; R. L. Mitchell, *Proc. Nutr. Soc.*, 1944, **1**, 183.

[3] For examples of the power of plants to concentrate rare earths, see W. O. Robinson, *Soil Sci.*, 1943, **56**, 1.

CHAPTER IV

QUANTITATIVE STUDIES ON PLANT GROWTH

In recent years attempts have been made to find mathematical expressions for the relationship between the quantity or concentration of plant nutrients present and the growth of the crop, and in particular its yield. Two types of solution of this problem are possible:

1. A hypothesis is set up which seems to fit the facts; it is expressed by an equation and this is then applied to the experimental data.

2. The experimental data are studied by statistical methods and an empirical equation or regression formula is fitted thereto, with no assumption or hypothesis as to the underlying causes.

Owing to the complexity of the problem—plant growth is dependent on so many factors—no general solution can be expected by either method. The first procedure has, in fact, been far more widely followed, and has been of more practical utility in the past than the second.

A number of different hypotheses have been put forward on the relationship between the amount of plant nutrient or other factors affecting plant growth and the growth or yield of the plant. One of the earliest was due to Liebig, who expressed it as the Law of the Minimum: the amount of plant growth is regulated by the factor present in minimum amount and rises or falls according as this is increased or decreased in amount. The relation between plant growth and the amount of the limiting nutrient present in the soil can, therefore, be represented as a curve such as is shown in Fig. 3: growth increases with additions of the limiting factor until it ceases to be

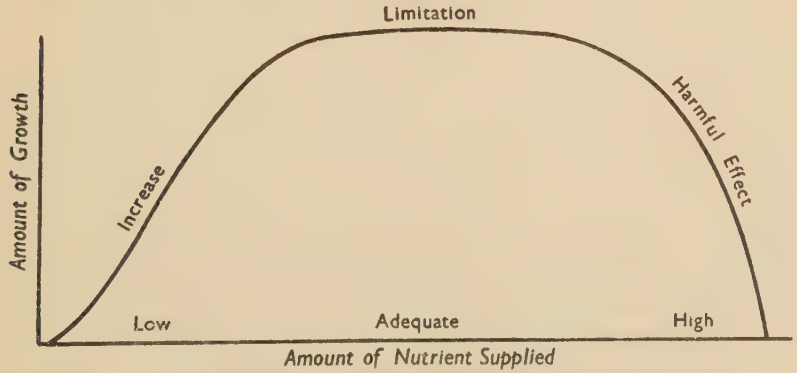


Fig. 3. General relation between any particular nutrient or growth factor and the amount of growth made by the plant.

limiting, then plant growth becomes independent of this factor as it increases still more until a point is reached when it is becoming toxic and causes plant growth to decrease. This law unfortunately has only a very limited validity, for if several factors are low, but none too low, increasing any one will increase the yield, as will be shown in the section on the interaction of nutrients.

The Relation between Growth and Nutrient Supply as found by Experiment

The first good experimental investigation was made by Hellriegel in the eighties of the last century. Barley was grown in pots of sand, all

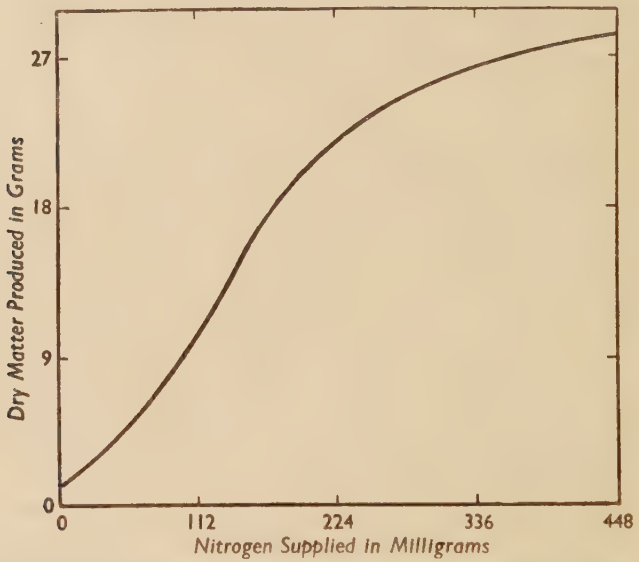


FIG. 4. Effect of increasing the nitrogen supply on the growth of barley.

necessary factors were amply provided, excepting only one nutrient salt, the amount of which varied in the different pots. Table 13 gives an example of his results: it shows the effect of increasing the nitrogen supply on the total dry matter produced and on other aspects of growth, and Fig. 4 shows the dry matter produced plotted against the amount of nitrogen supplied. The first increment of nitrogen produces a certain increase in yield, but the second and third increments produce proportionately more, thus giving a greater return than is expected if, as Liebig assumed, the effect be simply proportional to the amount present. The fourth and fifth increments, however, produce less effect. The curve, therefore, resembles an S and is described as sigmoid; this

is a common shape for curves showing total growth made after the lapse of a definite period of time, though perhaps less common for curves relating to environmental factors.

TABLE 13

Effect of increasing the Nitrogen Supply on the Growth of Barley in Sand Cultures: H. Hellriegel and H. Wilfarth[1]

Nitrogen given is calcium nitrate

Mgm. of nitrogen supplied	—	56	112	168	280	420
Dry matter in crop, gm.	0·74	4·86	10·80	17·53	21·29	28·73
Increased yield for each extra 56 mgm. nitrogen	—	4·12	5·94	6·73	1·88	2·97
Grain, per cent of dry matter in crop	11·9	37·9	38·0	42·6	38·6	43·4
Weight of one grain, mgm.	19	30	33	32	21	30

Field experiments can lead to similar results if the factor under consideration is at a sufficiently low level. The effect of increasing dressings of sulphate of ammonia on the yield of wheat on the permanent wheat field at Rothamsted is given in Table 14, both for the

TABLE 14

Response of Wheat to Sulphate of Ammonia Broadbalk Field[2]

	Grain yield				Straw yield			
Nitrogen supplied annually in manure, lb. per acre	0	43	86	129	0	43	86	129
Period, 1852–71								
Yield in cwt. per acre	9·5	14·9	19·9	21·7	14·9	24·5	35·4	41·3
Increase for each 43 lb. of nitrogen	—	5·4	5·0	1·8	—	9·6	10·9	5·9
Period, 1902–21								
Yield in cwt. per acre	7·0	11·1	16·2	19·2	10·5	19·0	30·6	39·5
Increase for each 43 lb. of nitrogen	—	4·1	5·1	3·0	—	8·5	11·6	8·9

twenty-year periods, 1852–71 and 1902–21. In both cases the second dose of nitrogen gives the largest response in the straw, and the same is true for the grain response in the latter period, but in the first twenty years, before the fertility of the unmanured had fallen very much, the response to the first dressing was rather larger than to the second.

[1] *Ztschr. Rübenzucker Ind. Beilageheft*, 1888.

[2] E. J. Russell and D. J. Watson, *Imp. Bur. Soil Sci., Tech. Comm.* 40, 1940. The plot receiving no nitrogen has received none since 1839 at the latest.

Thus the sigmoid curve does not always occur in field experiments, but perhaps only when the factor considered is at a very low level.

The Assumed Relation between Growth and Nutrient Supply

The smoothness of the curves found by experiment suggests that they can be expressed by a mathematical equation. E. A. Mitscherlich was among the first to do this, and his equation is certainly the best known and most widely used. He assumed that a plant or crop should produce a certain maximum yield if all conditions were ideal, but in so far as any essential factor is deficient there is a corresponding shortage in the yield. Further, he assumed that the increase of crop produced by unit increment of the lacking factor is proportional to the decrement from the maximum, or expressed mathematically:

$$\frac{dy}{dx} = (A - y)C,$$

where y is the yield obtained when x is the amount of the factor present, A is the maximum yield obtainable if the factor was present in excess, this being calculated from the equation, and C is a constant. On integration, and assuming that $y = 0$ when $x = 0$,

$$y = A\,(1 - e^{-Cx}).$$

This curve is not sigmoid in shape, but everywhere concave to the axis representing the nutrient supply. Mitscherlich's experiments were made with plants grown in sand cultures supplied with excess of all nutrients excepting the one under investigation. Table 15 shows the results

TABLE 15

Yield of Oats with Different Dressings of Phosphates. Mitscherlich[1]

P_2O_5 in manure	Dry matter produced	Crop calculated from formula	Difference	Difference expressed in terms of probable error.[2]
Grams	Grams	Grams	Grams	
0·00	9·8 ± 0·50	9·80	—	—
0·05	19·3 ± 0·52	18·91	− 0·39	− 0·8
0·10	27·2 ± 2·00	26·64	− 0·56	− 0·3
0·20	41·0 ± 0·85	38·63	− 2·37	− 2·8
0·30	43·9 ± 1·12	47·12	+ 3·22	+ 2·9
0·50	54·9 ± 3·66	57·39	+ 2·49	+ 0·7
2·00	61·0 ± 2·24	67·64	+ 6·64	+ 3·0

[1] *Landw. Jahrb.*, 1909, **38**, 537.
[2] If this figure is less than 3, the agreement is considered satisfactory.

obtained with oats and monocalcium phosphate. Mitscherlich claims to show by experiment that the proportionality factor C (called "Wirkungswert", or "faktor" in Mitscherlich's papers) is a constant for each fertiliser, independent of the crop, the soil or other conditions. If this were so an experimenter knowing its value could, from a single field trial, predict the yields obtainable from any given quantities of the fertiliser, a result of great practical value. Further, it would be possible to estimate by direct pot experiment the amount of available plant food in a soil, one of the most difficult of all soil problems.

Mitscherlich has, indeed, used his formula for this purpose,[1] and in his very interesting book[2] he applies the expression in a variety of ways. Some work of E. M. Crowther and F. Yates[3] furnishes a recent example of its use. By its aid they could put together in convenient tables all the results of fertiliser experiments that have been made on the various crops in Great Britain; and from these they formulated a suitable national war-time fertiliser policy for the country.

Mitscherlich's work was extraordinarily stimulating and caused a veritable flood of controversy when it was first developed. His equation has been of great practical value though it is certainly not exact. Thus, the "Wirkungswert" for a particular nutrient is not a constant but depends somewhat on the other conditions of growth. Further, the response curve is often sigmoid, fertiliser in excess decreases the crop yield, and the calculated maximum yield of the crop is sometimes far in excess of anything that can be obtained.

Other workers[4] have tried to improve on Mitscherlich's equation, and have had some success. But the interest in more exact equations has died down because the response of a crop to a fertiliser depends on many factors, such as the level of other nutrients present[5] and on the environmental conditions, so that no simple exact quantitative relation between the supply of a fertiliser and the crop response can exist.

The Interaction of Nutrients

The Law of the Minimum, namely, that the amount of plant growth is regulated by the factor present in minimum amount, and rises or falls according as this is increased or decreased in amount, implies that if two factors are limiting, or nearly limiting growth, adding only one

[1] *Landw. Jahrb.*, 1923, **58**, 601–17.

[2] *Bodenkunde für Land- und Forstwirte*, Berlin, 1913, and subsequent editions.

[3] *Emp. J. Expt. Agric.*, 1941, **9**, 77. For another recent example, see O. W. Willcox, *J. Amer. Soc. Agron.*, 1945, **37**, 10; 1949, **41**, 225.

[4] See, for example, B. Baule, *Landw. Jahrb.*, 1918, **51**, 363; 1920, **54**, 493; K. A. Bondorff, *Nord. JordbrForsk.*, 1923, **5**, 136; *Kgl. Vet. Landbohöjsk. Aarsskr.*, 1924, p. 293; E. A. Mitscherlich, *Ztschr. Pflanz. Düng.*, 1928, A **12**, 373; B. Balmukand, *J. Agric. Sci.*, 1928, **18**, 602.

[5] For a review of the work of plant physiologists on this subject, see F. G. Gregory, *Ann. Rev. Biochem.*, 1937, **6**, 557.

of them will have little effect on growth, whilst adding both together will have a very considerable effect. Two such factors are said to have a large positive interaction in such circumstances, for the response of the crop to both together is larger than the sum of the responses to each separately. If the crop response to the two factors together equalled the sum of its responses to each separately, we would say the two factors showed no interaction, or worked entirely independently of each other; and if the response to the two factors together was less than the sum of the responses to each factor separately, they are said to have a negative interaction with each other.

Two examples can serve as illustrations of such joint effects. The first is taken from a series of fertiliser experiments made at Rothamsted between 1938 and 1945, in which the response of potatoes to farmyard manure, sulphate of ammonia, muriate of potash and superphosphate is determined in all possible combinations of these fertilisers. Table 16 shows some of these responses for the three years 1939, 1943 and 1945, in which the crop only gave a low yield in the absence of fertiliser and manure.

This table shows that in the absence of farmyard manure, potatoes give a bigger response to nitrogen if the potassium supply is adequate than if it is short, and, similarly, a bigger response to potassium if the nitrogen supply is adequate. Thus, in the example given there is a positive interaction between these two fertilisers: nitrogen in the absence of potassium increases the yield by 0·4 ton, potassium in the absence of nitrogen increases the yield by 2·5 tons, and if given together the yield is increased by 4·3 tons, which is 1·4 tons larger than the sum of the nitrogen alone and potassium alone responses ($0{\cdot}4+2{\cdot}5=2{\cdot}9$ tons). On the other hand, provided adequate potassium was given, nitrogen gave an increase of between 1·8 and 1·9 tons per acre whether farmyard manure was given or not, whilst farmyard manure gave an increase of between 3·0 and 3·1 tons per acre whether nitrogen was given or not. These two materials thus act independently of each other, so that there is no interaction between them.[1] Potassium and farmyard manure provide an example of a negative interaction: in the presence of adequate nitrogen, potassium alone increases the yield by 3·9 tons per acre, and farmyard manure alone by 6·7 tons per acre, but the two together only increased it by 7·0 tons. Thus the response to potassium in the presence of the farmyard manure was only 0·3 ton, and the negative interaction between the two is 3·6 tons; in fact, in these experiments farmyard manure supplies all the potassium needed by the potatoes.

The second example illustrates the relationship between the water

[1] For other examples of this, see E. M. Crowther and F. Yates, *Emp. J. Expt. Agric.*, 1941, **9**, 77; A. W. Oldershaw and H. V. Garner, *J. Roy. Agric. Soc.*, 1944, **105**, 98.

TABLE 16

Response of Potatoes to Nitrogen and Potassium[1]

Yield of potatoes in tons per acre

Fertiliser	No N No K	N, No K	No N, K	N, K
No farmyard manure . . .	4·0	4·4	6·5	8·3
With farmyard manure . . .	9·3	11·1	9·5	11·5
Response to farmyard manure . .	5·3	6·7	3·0	3·1

	Response to nitrogen		Response to potassium		N K Interaction
	K absent	K present	N absent	N present	
No farmyard manure .	0·4	1·8	2·5	3·9	1·4
With farmyard manure.	1·8	1·9	0·2	0·3	0·1

	In presence of adequate potassium			
Response to	FYM alone 3·0	N alone 1·8	FYM+N 4·9	Interaction 0·1

	In presence of adequate nitrogen			
Response to . . .	FYM alone 6·7	K alone 3·9	FYM+K 7·0	Interaction —3·6

supply and the responsiveness of the crop to fertiliser, and in particular to nitrogen. C. von Seelhorst[2] at Göttingen made some pot experiments to establish this point nearly fifty years ago. The results of his experiment are given in Table 17, and they show that the oat crop could only respond to large dressings of nitrogen if the water supply was adequate.

This effect can be illustrated from some field experiments made by F. G. Gregory, F. Crowther and A. R. Lambert[3] in the Sudan. Table 18 shows that cotton can only make efficient use of a large supply of irrigation water if well manured with nitrogen, or, alternatively, that

[1] Dressings given:

	1939	1943 and 1945	
FYM	15	Mean of 8 and 16	tons per acre
N	0·8	0·6	cwt. N per acre given as sulphate of ammonia.
K	1·33	0·83	cwt. K per acre given as muriate of potash.

[2] *J. Landw.*, 1898, **46**, 52.

[3] *J. Agric. Sci.*, 1932, **22**, 617. See also F. Crowther, *Roy. Agric. Soc. Egypt, Tech. Bull.* 24, 1936.

it can only make good use of a high nitrogen supply if there is an adequate supply of irrigation water available.

TABLE 17

Influence of Water Supply on the Effectiveness of Manures on the Growth of Oats

Dry weight of oat crop in grams per pot

Manuring	Nitrogen series			Increased crop for	
	KP	KP, N	KP, 2N	First increment of nitrogen	Second increment of nitrogen
I. Moist soil . . .	67·5	68·5	68·5	1·0	0·0
II. Moister soil . . .	83·6	93·4	94·0	9·8	0·6
III. Wettest soil . .	99·5	119·5	135·0	20·0	15·5

K=0·83 gm. of K as K_2CO_3 per pot; P=0·44 gm. of P as $Ca(H_2PO_4)_2$ per pot; N=5 gm of N as $NaNO_3$ per pot.

Note.—The moist soil contained 14·35 per cent of water (41·6 per cent of saturation), the moister soil 15·41 per cent at the beginning, increasing to 18·43 (51·7 per cent of saturation) as the experiment proceeded, and the wettest soil 16·44 per cent at the beginning, increasing to 22·59 (63·7 per cent of saturation).

TABLE 18

Influence of Water and Nitrogen Supply on the Growth of Cotton

Yield of seed cotton in kantars per feddan[1]

Amount of sulphate of ammonia added	Rate of watering		
	Light	Medium	Heavy
None	1·38	1·54	1·58
300 lb. per acre	1·98	2·45	2·80
600 lb. per acre	2·28	3·04	3·79

There is a further aspect of the Law of the Minimum that may be extremely important when one is rectifying deficiencies. If crop growth is being severely limited by a few factors, and if, as is usual for most crops, one is interested in the yield of a part of the crop only, such as the grain for example, it will often happen that the maximum yield of this part of the crop is obtained by allowing the individual plants a large amount of space, so the root system of each plant can tap as large a volume of soil as possible. If one now rectifies the limiting deficiencies,

[1] 1 kantar per feddan = 300 lb. per acre.

it may also be necessary to increase the number of plants per acre to get the maximum possible increase in yield from this amelioration, for the individual plants will now need less volume of soil from which to get their nutrients. Further, it may also be necessary to change the variety of the crop grown, for it often happens that the variety best adapted to poor conditions has not the potentiality to make really good use of a liberal supply of nutrients, whilst varieties that can make very good growth in optimum conditions may be relatively less satisfactory when growing in poor conditions.[1] Table 19, taken from some work of B. A. Krantz[2] on the manuring of maize in North Carolina, illustrates the need for increasing the number of plants per acre if one is to get the maximum benefit from a high level of nitrogen manuring. Incidentally, this closer spacing has the desirable consequence that it helps to suppress weed growth which otherwise becomes troublesome when generous fertiliser dressings are used with wide spacing.

TABLE 19

The Influence of the Number of Maize Plants per acre on their Response to a Nitrogen Fertiliser

Yield of grain in bushels per acre

Number of Plants per acre	Pounds of Nitrogen per acre			
	20	70	120	170
4,000	39	52	59	57
7,000	39	58	67	65
10,000	41	65	69	72
13,000	36	59	73	73

Least significant difference 8·3 bushels per acre.
Plant numbers obtained by using spacings of 37·4 in., 21·4 in., 15·0 in. and 11·5 in. in rows 42 in. apart.

An important group of interactions between nutrients concerns those between the different cations in the soil and in the plant tissue. It has already been stated (see p. 28) that the leaves of plants tend to have a fairly constant total cation concentration in their dry matter, dependent mainly on the type of plant and to a much less extent on the soil and manuring. One important function of these cations is that of osmotic pressure and *p*H regulation, and for this purpose the composition of the cations present is largely irrelevant. But the leaves can only function properly if they contain a certain minimum concentration of the essential cations potassium, magnesium, calcium and the trace elements.

[1] For an example of this effect with sugar-cane, see J. A. Potter, *Trop. Agric. Trin.*, 1947, **24**, 94.
[2] *Better Crops with Plant Food*, 1947, No. 26.

Provided these minimal concentrations are exceeded, the relative concentrations of the different ions in the leaf are of little importance.[1]

The relative proportions of the cations in the leaf depend on the relative proportions of their available forms in the soil, a dependence that will be discussed in detail on p. 437. The point of immediate importance is that increasing the relative concentration of any one cation in the soil, as, for example, by adding a potassic fertiliser, will increase its concentration in the leaf, and in consequence decrease that of the other cations. If the plant is growing in a soil rather short of available magnesium, so that the magnesium concentration in the leaf is approaching the minimum required for healthy growth, then adding a potassium fertiliser may cause the magnesium concentration to fall below the minimum, so inducing a magnesium deficiency in the crop, which can be very severe if the crop growth is appreciably increased by the potassic fertiliser.[2] This phenomena is sometimes called an ionic antagonism, and in this particular example one would say that the potassium was antagonistic to the magnesium. These potassium-induced magnesium deficiencies can often be seen on fruit trees and market-garden and glasshouse crops growing on soils low in exchangeable magnesium, for all these crops commonly receive generous dressings of potassic fertilisers. In the same way salt added to a sugar-beet crop may induce magnesium deficiency in the crop.[3] It is important to realise that this is no reason for not using a potassic fertiliser or salt, if the crop responds to either, but it is a very good reason for using in addition a magnesium fertiliser, such as a dolomitic limestone if the soil is rather acid, or otherwise magnesium sulphate.

Large dressings of lime may also induce magnesium or potassium deficiencies in the crop if the soil is low in either. These effects for potassium are, however, most noticeable for some crops on calcareous soils. Thus C. A. Bower and W. H. Pierre[4] found that maize and some of the sorghums, for example, need a fairly high level of potassium in their leaves compared with calcium and magnesium, so usually respond to potassic fertilisers even if the level of available potassium in the soil is fairly high. On the other hand, sweet clover and buckwheat need a much higher level of calcium compared with potassium in their leaves, so are much less responsive to potassic fertilisers on these soils, whilst flax, oats and soybeans came intermediate between these two groups.

[1] For a review and discussion of this, see F. J. Richards, *Ann. Rev. Biochem.*, 1944, **13**, 611. For an example with lucerne, see A. S. Hunter, S. J. Toth and F. E. Bear, *Soil Sci.*, 1943, **55**, 61.

[2] For an example with potatoes, see T. Walsh and T. F. O'Donohoe, *J. Agric. Sci.*, 1945, **35**, 254.

[3] J. B. Hale, M. A. Watson and R. Hull, *Ann. Appl. Biol.*, 1946, **33**, 13.

[4] *J. Amer. Soc. Agr.*, 1944, **36**, 608.

A further example is furnished by the manuring of lucerne on soils rather low in calcium. If one manures lucerne generously with a potassic fertiliser, it will take up potassium in preference to calcium, so the potassium content of the leaves will rise and their calcium content fall:[1] a tendency which may be undesirable for feeding purposes as a calcium rich fodder is preferable to a potassium rich one. Hence lucerne growing on a non-calcareous soil rather low in exchangeable calcium should be given small and frequent dressings of the potassic fertiliser rather than a single large one.

[1] For an example of this, see F. E. Bear and S. J. Toth, *Soil Sci.*, 1948, **65**, 69.

CHAPTER V

THE COMPOSITION OF THE SOIL

Soils predominantly contain particles initially derived from the disintegration or decomposition of primary igneous rocks. But these particles may have been produced at an earlier geological period, moved by wind, water or ice over considerable distances, and been through one or more cycles of deposition and erosion. The processes that affect or alter these particles will be discussed in subsequent chapters, but one of the most fundamental is brought about by the plants that grow on the soil, for when the plants die they add to the soil energy-containing organic substances which they synthesised during their lifetime, and which serve as a food supply for a vast population of micro-organisms and even animals, which can in consequence inhabit the soil.

The soil mass is permeated with channels between the individual particles composing it, which are filled with water or air. The water, however, contains not only dissolved gases, but also some of the salts present.

Soils may, therefore, consist of four parts:

1. Mineral matter derived from the rocks, but more or less altered by decomposition or by the decomposition of the products of decomposition of other particles.

2. Calcium carbonate and phosphate and some resistant organic compounds derived from plants or organisms present at an earlier period.

3. Residues of plants and micro-organisms recently added to the soil.

4. The soil water, which is a solution of the various soluble and partially soluble salts present in the soil. Under temperate humid conditions this solution is dilute, but under some arid conditions, particularly in areas with poor drainage, it may become very concentrated. During dry periods such soils may contain appreciable quantities of soluble salts as crystals.

The soil has so far been pictured as consisting of a mass of particles, and this will be the aspect adopted in the rest of this chapter. But it must be realised that there is another aspect, of greater fundamental importance from the standpoint adopted in this book, namely, that of the soil as the medium for plant growth, and therefore as a medium for root development. From this aspect, the soil is a network of channels, filled with air and water and bounded by solid surfaces; and its

fundamental properties depend on the geometry of this interconnected network, called the pore space, on the properties of the bounding surfaces, and on the mechanisms which supply plant nutrients both to the water in these channels and also to the solid surfaces.

The geometry of the pore space depends very largely on the size distribution of the soil particles. If the particles are all very small, so that the pore channels between them are all very narrow or fine, the soil is called fine-textured; whilst if most of the particles are large, so that the pores are wide, or coarse, the soil is called coarse-textured. But these two types of texture are usually referred to by a different pair of adjectives—heavy and light. These words have nothing whatever to do with weight or mass, but with the power required to plough the soil, and it was measured by the number of horses needed on the plough, which varied from four on a heavy textured soil to one or two on a light. This is in fact a measure of the cohesion between particles of a moist soil, that is, of the force needed to separate neighbouring particles, and this, in turn, increases rapidly as the channels become narrower.

Soil texture is therefore a measure of the average size of the channels between the soil particles. But there is another property of the pore space that can be of great importance in some soils, particularly in medium to heavy textured soils, namely, their structure. Soils do not normally have all their particles absolutely evenly distributed throughout their volume, but have holes, such as those due to worms and old root channels running through their surface layers. Further, since many soils shrink on drying and swell on wetting, the soil particles tend to be clustered into aggregates or clods, with more or less vertical cracks, and sometimes horizontal ones, separating them. Hence the pore space of most soils does not only consist of a fairly regular network of channels but includes a certain number of irregularities, such as holes and extensive films of fairly uniform thickness (the cracks between clods); and the distribution of these irregularities depends on the structure of the soil. Hence Structure reflects the irregularities in the Texture: a well puddled soil has no structure but an even texture, and the more the puddled soil is weathered the more it acquires a structure.

Suitable and fairly simple techniques have been devised, by W. Kubiena[1] in particular, for examining the soil directly under a microscope, which allows one to see something of its texture, that is, of the kind of particles and organic matter present, and something of its structure, that is, how these particles are distributed throughout the soil mass. Thus one can make a rough estimate of the amount of plant material in the soil and its degree of decomposition, the shape of the

[1] *Micropedology*, Ames, 1938. See also *ForschDienst. Sonderh.*, 1942, **16**, 91, for technique, and *Soil Res.*, 1935, **4**, 380, for results.

larger mineral particles and how they are arranged in the soil, and to some extent how the finer particles are distributed; and in particular one can recognise the two principal types of microstructure in a soil, that in which the sand grains are comparatively clean and the finer particles are present in diffuse clusters between them, and that in which the sand grains have the finer particles cemented on to their surface.

The mineral matter itself can be divided into two parts—particles possessing a definite crystal structure, and inorganic material that cannot be so described. The latter is composed of ill-defined precipitates of hydrated oxides of iron, aluminium, manganese and possibly silicon also; the former consist of crystals derived from the original rock, which tend to be the larger particles, and crystals formed from the products of weathering, which are usually the smaller particles. For these reasons mere chemical composition of the soil in bulk rarely gives information of much value: one wants to separate out the composition of the ill-defined deposits from the mineral grains and, as will be shown later, of the finer from the coarser mineral particles.

Another mineral component of the soil has been assumed in the past to explain the property of base exchange in soils. H. S. Thompson, a Yorkshire gentleman, discovered in 1850[1] that soils had the power to absorb ammonia. He communicated this information to Thomas Way,[2] who was chemist to the Royal Agricultural Society of England; and they then independently discovered the even more surprising fact that when ammonium sulphate is washed through a soil, calcium sulphate and not ammonium sulphate is washed out. Way found that potassium salts behaved in the same way as ammonium, and concluded that there exists in the soil an active substance which, to quote his own words, "is really a salt of lime", arguing "that the retention of ammonia and potash by the soil could only be in the form of some insoluble salt of these alkalis, and could not have occurred without the existence of some similar salt of lime with which to interchange". He further showed that this salt of lime was connected with the clay and was destroyed by igniting the soil. No known simple silicates possessed these properties, but he prepared a number of "double silicates" of lime and alumina, etc., that did; thus they reacted, like clay, with ammonium salts to form an almost insoluble double ammonium silicate and a soluble calcium salt, and also, like clay, they lost this property after ignition. Although he did not establish the existence of such double silicates in the soil, their resemblance to the reactive constituent in the soil was so close that he considered himself justified in assuming their presence. It is interesting historically that an American, Edmund Ruffin of Virginia, had almost anticipated Way's discovery by twenty

[1] *J. Roy. Agric. Soc.*, 1850, **11**, 68. [2] *J. Roy. Agric. Soc.*, 1850, **11**, 313; 1852, **13**, 123.

years,[1] for he justified the idea that sour soils contained acids, even though they were insoluble, and that the function of calcareous manures was to neutralise this acidity. Once this idea is accepted, base exchange is a natural corollary.

Since that time many investigators have searched for the active constituent. The existence of Way's assumed "double silicates" was never established, but after the discovery that the properties attributed to them were actually possessed by the zeolites, a group of crystalline alumino-silicates found in cavities in igneous rocks or formed in the decomposition of felspars, it was assumed that zeolites must be present in the soil, and therefore must be the reactive bodies concerned. But zeolites were never shown to occur in the soil, and the whole supposition became unnecessary after Lemberg's discovery that many other silicate minerals besides zeolites are reactive, and exchange bases in salt solutions.[2] The seat of these exchange reactions has now been established to be the surfaces of the finer clay particles and some of the decomposition products of plant and microbial material in the soil, though a few soils may contain larger particles that possess this power.

Size Distribution of Soil Particles

Mere inspection of soil shows that it is composed of particles of different sizes possessing a greater or less tendency to stick together and form larger aggregates. These can be put into three groups, though the separation is not sharp or exact: clods, which are large and can be broken down by gentle mechanical means; crumbs and granules, which are smaller, but in which the particles are more tenaciously held, so that some gentle chemical treatment is necessary to separate them; and concretions in which the fine material is bound still more firmly by a cement containing inorganic colloids. The power of forming clods and crumbs resides partly in the organic matter and partly in the mineral particles of smallest size, of which a relatively small percentage suffices.

The first step in separating a soil into its component particles is therefore to overcome this cementing action, and this is done by grinding or crushing the aggregates until all the fine material has passed a 2-mm. sieve. This process, however, introduces an arbitrary element into the mechanical analysis of some types of soil. The concretions are usually very hard, and remain intact during mechanical

[1] *An Essay on Calcareous Manures*, Petersburg, Va., 1832. I am indebted to Dr. C. E. Kellogg for drawing my attention to this very interesting book.

[2] *Ztschr. Deut. Geol. Ges.*, 1870, **22**, 335, 803; 1872, **24**, 187; 1876, **28**, 537; 1877, **29**, 483. For a summary of this important investigation, see E. A. Fisher, *Trans. Faraday Soc.*, 1922, **17**, 305.

analysis, but in some soils they are soft enough to be more or less broken down by the preliminary grinding.

The second process consists in dispersing the fine aggregates, which is usually performed by oxidising the organic matter, removing calcium salts, such as carbonate and sulphate, and adding a dispersing agent which prevents the particles from sticking together. For many soils dispersing agents can be found that render the first two steps unnecessary: naturally they must be sufficiently gentle in action to avoid the destruction of any appreciable proportion of the soil material. All methods are conventional and differ slightly in their results, especially for calcareous soils containing large amounts of calcium carbonate, or for peat and fen soils containing 20 per cent or more of organic matter. The present international method gives satisfactory results for all soils that only contain small quantities of calcium carbonate or organic matter, for it requires that most of the organic matter be oxidised by boiling with hydrogen peroxide and the calcium carbonate removed by dilute hydrochloric acid. Obviously, the larger the proportion of either of these constituents in the soil, the smaller is the proportion of the mineral particles in the soil whose size distribution is to be determined.

Some method of specifying the size of the particles must be adopted. Microscopic examination shows that the particles have no simple geometrical shape: some may form thin flakes, and others are more or less spherical or cubic, but most of them are very irregular, and no simple measurement can adequately express their size. The mass and the volume are definable for the larger particles, but not for the fine colloidal particles; if, however, either of these could be determined experimentally it would afford an adequate measure of the size of the particles present. But there are no methods yet available for determining either mass or volume distribution of the particles.

The size of the soil particles must, therefore, be specified by some less fundamental property than their mass or volume. In practice, the property of the coarser particles selected for measurement is the ability to be retained by, or to pass through certain standard sieves, and of the finer particles their velocity of sedimentation in a vertical column of water at a standard temperature, usually 20° C. Since the settling velocities of the finest particles are below 10^{-6} cm. per second, it is often convenient to specify them by their negative logarithm, and to use the symbol *pv* for this quantity. Thus a particle having a settling velocity of 10^{-6} cm. per second has a *pv* of 6. But the result is usually given as the diameter of a sphere of density 2·6 that would, according to Stokes's law, have the same settling velocity. The fact that many of the particles do not happen to possess this density is no more disturbing than the fact that they are not spherical.

The particle sizes are usually classified into a few conventional groups whose limits, on different scales, are given in Table 20. On the present International Scale, a soil is divided into gravel, which is retained on a 2-mm. sieve, and fine earth, which passes this sieve. The fine earth itself is separated into coarse sand, fine sand, silt and clay, and the upper size limit of each of the first three fractions is ten times the lower size limit. The upper limit for the clay particles, 0·002 mm. diameter, is found to be a convenient division between the silt and clay, as particles larger than this usually only have typical clay properties weakly developed, whilst these properties usually are displayed with rapidly increasing intensity up to a certain limit as the particles get smaller. It was only because of this that the present International Scale was set up.

The coarse sand is separated on a sieve and the other groups by their different sedimentation velocities. The actual separation may be made by settling and decantation, or, much more rapidly, by taking samples with a pipette from a standard depth after standing for definite periods. Alternatively, the sands can be fractionated by elutriation, a method that has been much in favour on the Continent, and in which the soil is fractionated by means of an upward current of water, the velocity of flow being adjusted so as to balance exactly the corresponding sedimentation velocities.[1]

Fuller information about the size distribution of soil particles would be given by distribution curves, obtained not by dividing the soil up into four groups—coarse sand, fine sand, silt and clay—but into a large or even infinite number according to their settling velocities. Curves of this type were obtained by Sven Oden,[2] who suspended a pan of a balance in the suspension and devised a balance which automatically recorded the weight of sediment on the pan. Unfortunately the method contained an inherent error due to the impossibility of overcoming convection currents set up when the balance pan is suspended in a sedimenting column of a suspension.[3] E. G. Richardson[4] tried to overcome this error by measuring the opacity of the suspension to light; but the method has only limited use, as there is no general relation between the power of particles to scatter light and their size.

Attempts have also been made to determine the size distribution of the clay particles. A pipette technique has been devised by A. N. and B. R. Puri[5] in which very shallow sampling depths could be used, and hence comparatively short settling times, and E. W. Russell[6] showed

[1] These methods are described by H. Gessner, *Die Schlämmanalyse*, Leipzig, 1931.
[2] *Int. Mitt. Bodenk.*, 1915, **5**, 257.
[3] For a discussion of this whole method, see B. A. Keen, *Physical Properties of Soils*, London, 1931.
[4] *J. Agric. Sci.*, 1934, **24**, 457; *J. Appl. Phys.*, 1940, **11**, 653.
[5] *J. Agric. Sci.*, 1941, **31**, 171.
[6] *J. Agric. Sci.*, 1943, **33**, 147.

TABLE 20

Names and Sizes of Fractions obtained by Mechanical Analysis of Soils in Different Countries

Older British (replaced 1928)		American[1] (Bureau of Soils)		Older German Works[2] (Verband. Landw. Vers.-Sta.)		International (based on Atterberg)[3]	
Name of Fraction	Limits of Diameter of Particles, mm.	Name of Fraction	Limits of Diameter of Particles, mm.	Name of Fraction	Limits of Diameter of Particles, mm.	Name of Fraction	Limits of Diameter of Particles, mm.
Fine gravel	3–1	Fine gravel	2–1	Steine	above 5	Gravel (Kies)	above 2
				Grand	5–2		
				Sehr Grober Sand	2–1		
Coarse sand	1–0·2	Coarse sand	1–0·5	Grober Sand	1–0·5	Coarse sand	2·0–0·2
		Medium sand	0·5–0·25	Mittelkörniger Sand	0·5–0·2		
Fine sand	0·2–0·04	Fine sand	0·25–0·10	Feiner Sand	below 0·2	Fine sand (Mo, Feinsand)	0·2–0·02
		Very fine sand	0·10–0·05	Sehr feiner sand			
Silt	0·04–0·01	Silt	0·05–0·005	Mineralstaub		Silt (Schluff, Staub)	0·02–0·002
Fine silt	0·01–0·002	Clay	below 0·005	Ton			
Clay	below 0·002[4]	Colloidal fraction	below 0·002			Clay (Ton, Schlamm)	below 0·002

[1] L. B. Olmstead, L. T. Alexander and H. E. Middleton, *U.S. Dept. Agric., Tech. Bull.* 170, 1930. Except the "Colloidal fraction" the old grouping of Whitney is retained.

[2] *Landw. Vers.-Stat.*, 1894, **43**, 335. The first five fractions are separated by sieves, and the others in Kühn's sedimentation cylinder. Ramann adopted the American limits, but divided the clay into *Feiner Staub*, 0·005–0·0015 mm., and *Schlamm*, below 0·0015 mm.

[3] *Int. Mitt. Bodenk.*, 1912, **2**, 312. The international method is described in *Imp. Bureau Soil Sci., Tech. Comm.* 26, 1933.

[4] Probably smaller: the calculated value for the upper limit is 0·0014.

it could be used satisfactorily for particles with *pv* 6 or diameter 0·1 μ. Table 21 gives examples of results obtained by this method. An alternative technique, based on speeding up sedimentation by centrifuging the suspension, has been developed by C. E. Marshall,[1] who has given distributions down to particles with *pv* 6·7 or diameter of 0·05 μ. The centrifuge method is theoretically the better than the slow settling under gravity, as the finer particles, in virtue of their Brownian movement, diffuse slowly from the part of the suspension where they are concentrated to where they are dilute; that is, they are diffusing against

TABLE 21

An Extended Mechanical Analysis of some Clay Soils

	Sand	Silt	Clay	Per cent of the clay present in the fraction		
				pv 3·5–4·5 *d* 1·9–0·6 μ	4·5–5·5 0·6–0·19 μ	>5·5 >0·19 μ
Sudan Gezirah	16·6	14·1	54·9	9·6	9·1	81·2
Malayan Rubber—						
Clay type	10·1	5·0	81·0	6·5	62·1	31·4
Silt type	10·2	27·0	62·0	30·3	44·8	24·8
English Soils—						
Oxford Clay	15·6	31·3	47·7	16·7	17·4	66·0
Weald Clay	18·3	33·5	48·3	13·5	37·9	48·6
Hereford fruit	23·7	38·5	31·2	32·0	23·1	44·9

the direction of settling. This effect blurs the sharpness of the separation between different particle sizes, but it becomes increasingly small as the gravitational field is increased. In practice, since clays contain particles of a wide variety of sizes, this complication does not appear to be serious in the ranges given. These techniques also are only of value if the clay particles have definite size, reasonably independent of the method of dispersion used, a condition that does not apply to clays composed of some montmorillonite-type particles (p. 88).

In practice, accurate mechanical analysis of soils has not proved of great value. One needs to group soils into various "textural" classes,[2] such as sands, loams or clays, but the number needed is usually limited, and an experienced field worker can distinguish ten or more[3] fairly

[1] *Proc. Roy. Soc.*, 1930, **126** A, 427; *J. Soc. Chem. Indust.*, 1931, **50**, 444 T; *Proc. Soil Sci. Soc. Amer.*, 1939, **4**, 100.

[2] Texture in this connotation refers to the size distribution of the soil particles: thus one would say a soil has a clay or a loam texture in this use of the word.

[3] For a description of the various textural classes used by the British and American field workers, see G. R. Clarke, *The Study of the Soil in the Field*, 3rd ed., Oxford, 1941; C. E. Kellogg, *U.S. Dept. Agric., Misc. Publ.* 274, 1937.

easily by feeling the soil when wet between his fingers. Mechanical analysis is useful in checking this method, but for some soils the two methods—fingers and analysis—give appreciably different answers; and in these cases the field behaviour is usually better specified by the finger behaviour than the mechanical analysis. This discrepancy is due to the differences in the shapes of the finer particles, and also to the different behaviour to water of the various clay minerals that can be present in the soil.

The Mineralogical Composition of the Soil Particles

SAND AND SILT FRACTIONS

These particles can be divided into two main groups: crystalline mineral particles derived from primary rock and rock fragments; and micro-crystalline aggregates composed, for example, of calcium carbonate or ferric or aluminium hydroxides which have been formed either from products of weathering or from residues of plant and animal life. There may also be present some crystals such as calcite formed in the soil itself, perhaps crystals of some other minerals formed during the weathering process, and perhaps non-crystalline or poorly crystalline residues of the weathering of rock minerals, such as biotite.

The principal minerals found in the silt and sand fraction of the soil[1] are:

I. Quartz.

II. Felspars.

(*a*) microcline and orthoclase[2] $KAlSi_3O_8$, which are potash felspars. Both are resistant to weathering, microcline being the more resistant;

(*b*) plagioclase, a series of mixed crystals having albite or soda felspar $NaAlSi_3O_8$ and anorthite or calcium felspar $CaAl_2Si_2O_8$ as end members. The sodium rich members are about as resistant to weathering as orthoclase, whilst the calcium rich members weather more easily.

III. Micas.

(*a*) containing no divalent metals; muscovite, a potassium aluminium silicate, $H_2KAl_3(SiO_4)_3$, which is fairly stable;

(*b*) containing divalent metals; biotite, a potassium magnesium iron aluminium silicate not very resistant to decomposition. No true micas containing calcium are known, and soda mica is very rare;

[1] For details, see for example H. B. Milner, *Sedimentary Petrography*, 3rd ed., 1936, London; A. N. Winchell, *Elements of Optical Mineralogy*, 5th ed., New York, 1937.

[2] The following formulae are given only to show the type of constitution. The composition of actual specimens may differ considerably from the type formula.

(*c*) glauconite; a potassium iron silicate closely related to mica.

IV. Pyroxenes and Amphiboles, a complex group containing typically magnesium calcium iron silicates, not very resistant to decomposition.

V. Various minerals, such as zircon, garnet, apatite (see p. 449), ilmenite $FeTiO_3$, the iron oxides haematite Fe_2O_3, and magnetite Fe_3O_4, and the hydrated oxide limonite $FeO(OH),nH_2O$.

Quartz is by far the commonest mineral in most soils, and also the most resistant to decomposition. In soils derived from sedimentary deposits it often makes up 90 to 95 per cent of all the sand and silt particles.[1] Soils directly derived from primary rock contain much less, the actual quantity depending on the quartz content of the rock itself and the amount of weathering it has been subjected to. J. Hendrick and G. Newlands[2] have, for example, found some Aberdeenshire soils derived from a basic igneous olivine-gabbro which are practically quartz-free, and the other soils in their paper illustrate the rapid rise in quartz content to over 70 per cent if the soil has been derived from rock which has already been subjected to weathering. Table 22, which is taken from some results of R. P. Humbert and C. E. Marshall,[3] illustrates this effect by giving the distribution of quartz and felspar in the sand and silt fraction down the profile of a soil derived from granite.

TABLE 22

Distribution of Quartz and Felspar in the Sand and Silt Fraction of a Soil derived from Granite

Depth in inches . .	0–4	4–10	10–18	18–24	Rotten Rock	Un-weathered Rock
Quartz in fraction (%) .	50	45	30	25	25	32
Felspar in fraction (%) .	28	30	27	36	65	53

[1] This is in marked contrast with the content in the average parent rock material, which according to F. W. Clarke is:

	Per cent
Felspars	60
Amphiboles and Pyroxene .	17
Quartz	12
Micas	4
Other minerals	7
	100

(analyses of 700 igneous rocks).

He further estimates that the lithosphere is composed of 95 per cent igneous rocks and 5 per cent sediments down to a depth of half a mile (*U.S. Geol. Surv., Bull.* 770, 1924).

[2] *J. Agric. Sci.*, 1923, **13**, 151.

[3] *Missouri Agric. Expt. Sta., Res. Bull.* 359, 1943.

THE CLAY FRACTION

The clay fraction is typically differentiated mineralogically from the silt fraction by being composed predominantly of minerals which are formed as products of weathering and which are not found in unweathered rocks. These minerals rarely ever occur in particles larger than 2 μ, and are usually present as particles smaller than this. They are much more resistant to weathering in the soil than are rock minerals ground to a comparable particle size, and they comprise the particles that carry the physical and chemical properties characteristic of clays.

The coarser clay fractions, particularly those larger than 0·5 μ in diameter, may contain appreciable proportions of quartz and sometimes of mica, but the fractions finer than 0·1 μ are almost entirely clay minerals or other products of weathering, such as hydrated ferric, aluminium, titanium, manganese and silicon oxides.

The great difficulties in making a mineralogical analysis of clay particles are that X-ray photographs cannot be taken of single crystals as they are too small, and the crystals themselves possess such a low symmetry that X-ray powder photographs can only give limited information. Other types of method[1] are, however, also available. These minerals are all hydrated and lose their water at different temperatures, hence they can to some extent be differentiated by their dehydration curves. The energy change involved as this water is lost, and other changes which occur in the clay mineral, are most marked in certain critical temperature ranges, which are characteristic for different minerals. Again, some clay mineral particles have characteristic shapes: they may be flat with sharp edges, or have blurred edges, or be rod-shaped, and these can be determined by photographing the particles in the electron microscope.

The result of all this work has been to show that for many soils the clay particles do not all belong to one definite and clearly defined class; they appear either to be a mixture of particles belonging to different mineralogical groups, or even for each particle itself to be a mixture of groups. The main groups present are of the kaolinite, montmorillonite and illite types; but because of the apparent complexity of the minerals composing the finer soil clay particles, much work is being done on these simpler type-minerals, which are only found in the pure state in certain very restricted localities. For this reason the composition and properties of these type-minerals will be discussed in the next chapter.

[1] For discussions of the different methods available and their limitations, see G. Nagelschmidt, *J. Agric. Sci.*, 1939, **29**, 477; *Imp. Bur. Soil Sci., Tech. Comm.* 42, 1944; W. P. Kelley *et al.*, *Soil Sci.*, 1939, **48**, 201; S. B. Hendricks and L. T. Alexander, *Soil Sci.*, 1939, **48**, 257; W. F. Bradley, *Amer. Miner.*, 1945, **30**, 704.

NON-CRYSTALLINE INORGANIC COMPONENTS OF SOILS

The soil contains other material beside the definite mineral particles. The main additional component is organic matter, which will be considered later. But there is also present other inorganic material of very indefinite composition. If one examines the sand grains of many soils under a microscope, their surfaces are seen to be coated with an opaque layer, or to have opaque spots on their surface, and these will often persist after all organic matter has been oxidised. This surface matter can be dissolved in suitable acids, and it is found to contain aluminium, iron and silicon.

The earlier workers, such as J. M. van Bemmelen,[1] tried to separate the products of weathering from the unweathered products by digesting the soil with hydrochloric or sulphuric acid of definite strength; and the digestion with boiling hydrochloric acid was very widely used in Europe, but interest in these methods has died down since the discovery that clay particles are crystalline, and that the acids attack an indefinite proportion of the clay minerals as well as the non-crystalline inorganic precipitates.

The first modern attempt to dissolve out the non-clay amorphous material was made by O. Tamm[2] when he introduced half-neutralised ammonium or sodium oxalate solutions. These dissolve iron and aluminium, and to a less extent silicon, hydroxides without seriously attacking the clay minerals. Since then E. Truog[3] and his co-workers introduced first hydrogen sulphide and then nascent hydrogen as solvents for iron hydroxides, and probably also for iron in indefinite combination with aluminium or silicon hydroxides. By these means the mineral particles, even fine clay particles, can have their surfaces cleaned up so that the exposed surface belongs to the crystal lattice.

The cleaning up of the clay mineral particles by these techniques when properly carried out allows sharper X-ray photographs to be taken, increases the apparent proportion of fine clay particles present in the soil, and often also the base exchange capacity of the soil. All these together are good evidence that there has been no appreciable attack on the clay minerals themselves, although, as Dion points out, these methods are less satisfactory if the clay mineral is itself rich in iron—a very rare occurrence in the clays present in soils.

The colour of the finer fractions of the soil is radically altered by cleaning up, for they become a uniform greyish white. The typical colour of mineral soils, in so far as it is not due to organic matter, is

[1] *Landw. Vers.-Stat.*, 1877, **21**, 135; 1878, **23**, 265; 1888, **35**, 69; *Ztschr. anorg. Chem.*, 1904, **42**, 265.

[2] *Medd. Skogsförsöksanst.*, 1922, **19**, 385; 1934, **27**, 1.

[3] *Proc. Soil Sci. Soc. Amer.*, 1936, **1**, 101; with M. Drosdoff, *J. Amer. Soc. Agron.*, 1935, **27**, 312; *Soil Sci.*, 1935, **39**, 463. For recent modifications, see C. D. Jeffries, *Soil Sci.*, 1941, **52**, 451; H. G. Dion, *Soil Sci.*, 1944, **58**, 411.

in fact due to iron compounds, and depends both on their micro-crystalline form, that is, whether they are of the haematite, goethite or other form, and on the fineness of their subdivision. The iron compounds can probably also form complexes with some fraction of the organic matter giving brown to black colours, the black being characteristic of alkaline or else reducing conditions, but these conditions do not necessarily ensure that these black-coloured compounds are developed.

The Exchangeable Bases Held by the Soil

These are the bases that H. S. Thompson and Thomas Way investigated. They can be displaced from the soil and determined by washing the soil with a salt solution not containing a cation present among the exchangeable bases—such as barium or ammonium; or by washing the soil with a dilute acid solution, such as 0·05 *N* hydrochloric acid or 0·5 *N* acetic acid; or they can be removed by electro-dialysing the soil, that is, by allowing the cations to move in an electric field through a membrane which can hold back all clay particles. However, none of these methods may be suitable if the soil contains soluble salts, and the last two may be unsuitable if it contains calcium or magnesium carbonates.

The exchangeable bases held by a soil are usually expressed as the number of milli-equivalents of the base held by 100 gm. of dry soil. This unit, which is almost universally used, has not been given a name, though E. M. Crowther suggested it should be called a "Way". Neutral soils hold from 5 way or less, if they are sandy, 40–60 way if they are heavy; and some clays and peats can hold up to 100 way or more. Average figures for a number of types of soil are given in the last line of Table 23.

In the temperate regions and in neutral soils, calcium is the predominating exchangeable base, accounting for 80 per cent or more of all the exchangeable bases present in the soil. Magnesium is usually the second commonest, making up 10 to 15 per cent, and sodium and potassium make up a few per cent each. This can be seen for the composition of the exchangeable bases of a number of soils given in Table 23. Other cations besides these four are present, but they are usually only present in very small quantities. In acid soils these bases are replaced probably by hydrated aluminium, but this problem will be discussed on p. 94. Soils in which strongly reducing conditions occur, such as some water-logged soils, may also contain appreciable proportions of exchangeable ferrous ions.

The quantitative laws governing base exchange will be discussed on p. 110, but a simple and fruitful picture of the process is found in the

TABLE 23

Percentage Composition of Exchangeable Bases from Various Acid or Neutral Soils

	Chernozem, U.S.S.R.	Podzol, U.S.S.R.	Clay, Holland	Sandy humus, Holland	Various, Scotland	Various, California	Rothamsted, England	Woburn, England
	(*a*)	(*a*)	(*b*)	(*b*)	(*c*)	(*d*)	(*e*)	(*f*)
Ca	82·1	80·5	79	76	83	63	92	79
Mg	15·1	13·4	13	13	7	25	5	13
K	2·7	6·1	2	3	2	4	3	3
Na	Nil	Nil	6	8	3	8	—	5
Total in mgm. equiv. per 100 gm. soil[1]	54·8	6·2	38·3	19·8	11·2	30·3	14·7	5·2

(*a*) K. K. Gedroiz, *Koll. Chem. Beih.*, 1929, **29**, 149.
(*b*) D. J. Hissink, *Int. Mitt. Bodenk.*, 1922, **12**, 81. Average of twenty-five clay soils and two sandy soils.
(*c*) Average of seventeen soils, A. M. Smith, *J. Agric. Sci.*, 1925, **15**, 466.
(*d*) Average of seven neutral soils, W. P. Kelley and S. M. Brown, *Calif. Agric. Expt. Sta., Tech. Paper* 15, 1924.
(*e*) Broadbalk soil, Rothamsted, after continuous cropping with wheat without manure for eighty years, H. J. Page and W. Williams, *Trans. Faraday Soc.*, 1925, **20**, 57.
(*f*) Woburn soil, average of four plots after continuous cropping with wheat or barley without manure for fifty years, E. M. Crowther and J. K. Basu, *J. Agric. Sci.*, 1931, **21**, 689.

work of G. Wiegner.[2] Following Duclaux, he considered the clay particles holding the exchangeable bases are micelles carrying a negative charge which must be neutralised by the exchangeable ions, and he represented the process of base exchange diagrammatically thus:

$$\boxed{\begin{matrix}\text{Clay}\\ \text{Micelle}\end{matrix}}\begin{matrix}\text{Ca}\\ \text{K}\end{matrix} + 3\ \text{NaCl} \longrightarrow \boxed{\begin{matrix}\text{Clay}\\ \text{Micelle}\end{matrix}}\begin{matrix}\text{Na}\\ \text{Na}\\ \text{Na}\end{matrix} + \text{CaCl}_2 + \text{KCl}.$$

[1] i.e. the sum of the separate bases as determined.
[2] Wiegner summarised his views in *J. Soc. Chem. Indust.*, 1931, **50**, 55 T, 65 T and 103 T, and finally in his address to the International Society of Soil Science at Oxford, 1935 (*Trans. 3rd Int. Cong. Soil Sci.*, **3**, 5). This was his last important discourse: on receiving the reprints, he said, "Siehst du, in *dem* Vortrag steckt meine ganze Lebensarbeit auf bodenkundlichem Gebiet."

CHAPTER VI

THE CONSTITUTION OF CLAY MINERALS

All the clay minerals occurring in the soil are probably built out of sheets, or layers, of oxygen atoms, and so belong to the class of layer-lattice minerals.[1] Only two types of layer lattices have been recognised in these clay minerals, that found in the kaolinite and that in the montmorillonite type.

All clay minerals are built out of two definite building units, namely, four oxygens at the corners of a tetrahedron usually with a silicon atom in the centre, and six oxygens at the corners of an octahedron, often with an aluminium at the centre. The silicon is thus in 4-co-ordination and the aluminium in 6-co-ordination.

The silicon-oxygen tetrahedra are bound together by three of the oxygens of each tetrahedron being linked to a second silicon atom. Each tetrahedron is thus linked to three others in such a way that three out of the four oxygens in each tetrahedron lie in a plane in hexagonal packing, as shown in Plate III. It is believed that all the silicons and the remaining oxygens lie on the same side of the oxygen layer, but it is possible that they may lie on either side in some clay minerals. This sheet has the unit composition $2(Si+O+\frac{3}{2}O)=Si_2O_5^{--}$, hence carries one negative charge per silicon atom; for each silicon atom is attached to one oxygen atom out of the plane and to three shared atoms in the plane.

The octahedral units are linked together as in the minerals gibbsite $Al(OH)_3$ and brucite $Mg(OH)_2$ by forming two layers of hydroxyl ions in closest packing. Between these two layers are the octahedral holes, each of which contains a magnesium ion in brucite, but, as is shown in Plate III, only two-thirds contain an aluminium ion in gibbsite. This double sheet is thus electrically neutral for each mineral. Further, it can be seen that in brucite every hydroxyl touches three magnesium ions, whilst in gibbsite, owing to the empty holes, each hydroxyl usually only touches two aluminium.

Clay minerals of the kaolinite group consist of sheets each built out of a silicon-oxygen layer in open hexagonal packing and a gibbsite layer fused with it so that the tetrahedral oxygens lying out of the main

[1] For a recent review of this subject with many photographs of the structure of clay crystals, see C. E. Marshall, *The Colloid Chemistry of Silicate Minerals*, New York, 1949. W. L. Bragg's book, *Atomic Structure of Minerals*, London, 1937, is the standard text-book on the fundamental structures of soil and clay minerals.

plane form part of one layer of the gibbsite structure. Thus minerals of this type consist of three layers: a layer of oxygens in open hexagonal packing, a layer of oxygens and hydroxyls in close packing, and a layer of hydroxyls in close packing. In the centre layer two-thirds of the ions are oxygen, as shown in Plate III, i.e. those forming tetrahedra with the hexagonal sheet and touching silicon ions, and one-third hydroxyls, and these come above and in the centre of the hexagonal holes. The sheet is therefore unsymmetrical and electrically neutral.

Clay minerals of the montmorillonite group consist of a gibbsite layer condensing with two silicon oxygen layers, one on either side, as is shown in Plate III. A unit sheet of these minerals therefore consists of four oxygen layers, the first being the one in hexagonal packing, then two in close packing, in which two-thirds of the ions in each layer are oxygen and one-third hydroxyl ions, and finally another silicon-oxygen layer. The sheet is therefore symmetrical and electrically neutral; and behind each hexagonal hole on the two surfaces lies a hydroxyl ion. The type-mineral having this structure and constitution is pyrophyllite.

Two factors are needed to describe the way the sheets are piled one on top of the other. One is the distance between similar layers in adjacent sheets—the basal spacing of the structure; and the other is the relative positions of the oxygen atoms in corresponding layers of adjacent sheets, for given the basal spacing one can still displace or rotate one sheet relative to its neighbour. In the two kaolinite minerals, nacrite and dickite, adjacent sheets take up fixed positions, so that the crystal has three-dimensional symmetry, although the symmetry in the plane perpendicular to the basal spacing is low. In these minerals adjacent sheets are held together by hydrogen bonds; for if a hydroxyl layer of one sheet lies close enough, and in the right relative position to the hexagonal oxygen layer of its neighbour, hydrogen bonds will develop between the hydroxyl and the contiguous oxygen ions, allowing crystals up to 1 μ or so in size to form, as shown in Plate III. In the kaolinite minerals of the halloysite type, however, the neighbouring sheets have no fixed positions relative to each other, hydrogen bonding is therefore impossible and there are no strong forces present to hold them together.

There are also no strong forces present to hold adjacent sheets of minerals of the pyrophyllite type together, since the outer layers of these minerals only contain oxygen and not hydroxyl ions. Thus both halloysite and pyrophyllite can only exist in very small particles a single sheet thick (see Plate III), and this has the consequence that whereas nacrite and dickite possess a definite basal spacing of about 7·1 Å., halloysite and pyrophyllite do not. These latter minerals can only have a basal spacing if they are dried from a suspension in such a way

that the individual sheets all lie parallel to one another. A sample of halloysite prepared in this way will have a basal spacing of 7·1 Å., as in nacrite and dickite, but as soon as a little water is added it will come between the sheets and increase the spacing between them. As will be mentioned later, this behaviour is typical of the montmorillonite minerals and is due to the absence of strong forces between adjacent sheets.

The structure of clay minerals is thus seen to be dominated by the oxygen layers: the metal ions merely fit into certain holes between the oxygens. The minerals can therefore only exist if the metal ions present fit into these holes without causing too much distortion in the oxygen layers. Now the radius of the largest ion that can just fit into the tetrahedral space between the four contiguous oxygens is 0·225 times the radius of the oxygen ion, and into the octahedral space between six oxygens is 0·414 times the oxygen radius.[1] Table 24 gives

TABLE 24

The Radii of Certain Ions in 6-co-ordination (after Pauling)

Radii in Ångstrom units (10^{-8} *cm.*)

O^{2-} 1·40			
4+	3+	2+	1+
Si 0·41	Al 0·50	Mg 0·65	Li 0·60
	Fe 0·60	Ni 0·70	Na 0·95
	Mn 0·62	Fe 0·75	K 1·33
	Cr 0·64	Mn 0·80	NH_4 1·48
	V 0·66	Ca 0·99	

the values of the ionic radii of a number of elements when in 6-co-ordination, and it can be seen that aluminium is the only ion small enough to fit into the octahedral space: its radius relative to oxygen is 0·36, whilst that of the next smallest common ion, ferric iron, is 0·43, and hence is just too large for this space. The ionic size of silicon in 4-co-ordination is not certain, but is sometimes about 0·38 Å., which gives a radius relative to oxygen of 0·27, which is too large for the tetrahedral hole; but its radius must be smaller than this in this lattice for it fits into these holes with little disturbance to the spacing of the oxygen ions. Thus silicon and aluminium are the only common ions capable of filling these holes without disturbing the arrangement of the oxygen layers, and they are, in fact, the only ions that have been

[1] These figures as well as Table 24 are taken from A. F. Wells, *Structural Inorganic Chemistry*, Oxford, 1945.

found in the kaolinite type of clay mineral built out of sheets containing three oxygen layers. These minerals are very stable in the soil, being extremely resistant to weathering.

The four-layer lattice differs from the three-layer in that ions other than silicon and aluminium are found in these holes; hence the oxygen layers in this lattice can suffer some distortion without losing stability. It is an interesting fact, not yet properly explained, that the mineral having only silicon ions in the tetrahedral holes and aluminium in the octahedral, and thus carrying no net charge, has not been recognised among those occurring in soil clays. The replacement of these two ions by others is known as isomorphous replacement,[1] as the distortion is not sufficient to affect the lattice constants appreciably. The only ion that has been recognised to replace silicon in the tetrahedral holes is aluminium, and it may replace up to one-fifth of the silicons, although the proportion is usually considerably lower than this. However, in mica, which is formed at high temperatures, when the holes will be correspondingly larger, one-quarter of the silicon is replaced. Many metals can replace aluminium in the octahedral holes, but they either only replace a small proportion, presumably because, since they are all larger than aluminium, they would otherwise distort the lattice so much it would lose stability,[2] or else they replace almost all the aluminium, thus increasing the spacing between the two close-packed oxygen layers. Ferric iron and magnesium are the commonest replacers, but small proportions of ferrous iron, zinc, manganese, chromium, nickel and lithium may also be found in the octahedral holes, whilst potassium, calcium and sodium do not enter into these holes, because of their size.[3] Isomorphous replacement of aluminium in these conditions does not have any large affect on the number of ions in the octahedral holes; it remains between 2·0 and 2·2 atoms per three holes. If the main replacement is that of silicon by aluminium the mineral is sometimes referred to as a beidellite, whereas if the main replacement is that of octahedral aluminium by magnesium, or if both replacements take place, it is a montmorillonite. No minerals have a large replacement in both the octahedral and tetrahedral positions, presumably because this would cause too much distortion of the lattice. Further, the lattice appears to have some small internal electrical compensation, for as the replacement of silicon by aluminium, or of a divalent ion for

[1] Isomorphous replacement occurs when the crystal lattice is being formed. It cannot occur afterwards because the ion cannot get out of the hole. It is thus quite distinct from base exchange, where the ions are outside the surface of the lattice.

[2] It is interesting to note that silicon never replaces aluminium, presumably because if the ion in the space is too small the lattice again loses stability.

[3] For a recent review of this subject, see C. S. Ross and S. B. Hendricks, *U.S. Geol. Surv., Prof. Paper* 205 B, 1945; *Proc. Soil Sci. Soc. Amer.*, 1942, **6**, 58. These papers give examples of analyses of clay minerals to illustrate the range of replacements found.

aluminium increases, so the number of octahedral holes containing ions tends to rise.

A few minerals exist in which all the octahedral aluminiums are replaced. Nontronite has them all replaced by ferric iron; talc and saponite have all, not two-thirds, of the octahedral holes filled with magnesium, and sauconite has them all filled with zinc. Talc differs from saponite in that it has all the tetrahedral holes filled with silicons, whilst saponite has 15 to 20 per cent replaced by aluminium. But these minerals are much less resistant to weathering and to chemical reagents than those containing predominantly gibbsite layers, and they have not been recognised in soil clays.

Isomorphous replacement has a very important consequence for the properties of the clay minerals, for it may, and usually does, lead to the crystal lattice having a net negative charge. Thus, each replacement of an aluminium for a silicon, or of a magnesium for an aluminium, causes the negative charge on the lattice to increase by a unit. These charges are neutralised by the cations, which form the exchangeable bases held by the clay mineral.

Ross and Hendricks point out the interesting fact that all the clay minerals of this four-oxygen layer type that have been considered in the above paragraphs either possess no net negative charge per sheet, as, for example, talc and pyrophyllite, or they have one-third of a negative charge per unit cell. Thus, if the uncharged cell is written $(Al_2)(Si_4)O_{10}(OH)_2$, isomorphous replacement of the aluminium and silicon always seems to have taken place so as to leave one-third of a negative charge on this unit, which corresponds to about 85 milli-equivalents per 100 gm. of clay mineral. The possession of an appreciable base exchange capacity, or negative charge on a clay particle, is, in fact, a consequence of isomorphous replacement. Thus kaolinite, which has only a small net negative charge of about 4 milli-equivalents per 100 gm., can have little isomorphous replacement in its lattice.

Montmorillonite type-minerals having isomorphous replacement can, however, be built up into crystals of higher symmetry if adjacent sheets take up definite positions, and this gives a group of clay minerals that commonly occur in the soil which are variously known as illite, bravaisite or hydrous mica. Their structure can best be understood from that of muscovite. This mica has aluminium in the octahedral holes and also one-quarter of the silicon is replaced by aluminium, and the excess negative charge on each sheet is balanced by potassium ions lying in the hexagonal holes between two sheets, for the sheets are so superimposed that the hexagonal holes come opposite one another. Thus, each potassium ion touches twelve oxygens, six in each hexagonal

layer, and two hydroxyls, one in each of the gibbsite layers, for it just fits into this hole. The potassium ions lie in a regular pattern on the hexagonal oxygen layers, hence each layer has a fixed position relative to its corresponding layer in adjacent sheets, thus the mica has a higher crystal symmetry than the clay minerals.

The illite group of clay minerals have a structure somewhat similar to mica, but the sheets carry a smaller negative charge as a lower proportion of the silicons are replaced by aluminium, and little replacement of the octahedral aluminium seems to occur. But only part of this charge is neutralised by potassium ions, which are therefore much fewer and less regularly spaced than in the mica. The forces holding adjacent sheets together are therefore weaker, and the clay crystals themselves smaller and less regular. The net negative charge on these clay particles is therefore smaller than in the montmorillonite group because a portion of the charge is neutralised by these bonding potassium ions: it usually lies between 20 and 40 milli-equivalents per 100 gm.

The minerals occurring in the clay fraction of agricultural soils may differ from the type-minerals described, in that isomorphous replacement may not be uniform throughout a sheet, successive sheets may also differ in composition, and one particle may have a few sheets held together weakly by potassium ions and a few not so held, hence displaying the properties of both the illite and montmorillonite type of mineral.[1] In fact, for the clay minerals of the beidellite type that occur in soils, the higher the proportion of silicons that are replaced by aluminium the greater the amount of potassium held in non-exchangeable form and the more the clay becomes of the illite type.

Montmorillonites differ from illites in that there are no strong bonding forces holding adjacent sheets together. But it is not at all clear why potassium does not bond montmorillonite into illite, nor is it clear why montmorillonite should be formed at all if any potassium is present when it is being formed. It is possible that montmorillonite is only formed in soils under conditions of a very low potassium ion concentration, and this may be the reason that so few soils appear to contain it. But it is also possible that montmorillonite, as distinct from beidellite, cannot hold potassium ions really tightly in the hexagonal holes because its negative charge is due to isomorphous replacement inside the gibbsite layer, with the consequence that the attractive force on the potassium may be considerably less than if the replacement of silicon occurs in the outer layer.

Montmorillonites are thus characterised by having all their negative charges accessible to the liquid in which they are dispersed. This has

[1] S. B. Hendricks and L. T. Alexander, *Soil Sci.*, 1939, **48**, 257; S. B. Hendricks and E. Teller, *J. Chem. Phys.*, 1942, **10**, 147; R. E. Grim and R. A. Rowland, *Amer. Miner.*, 1942, **27**, 746, 801.

two consequences. Any cation, whatever its size, can neutralise all the negative charges on a montmorillonite, and in particular the basic group in proteins can neutralise this charge. And secondly the exchangeable cations around the particle attract water molecules to themselves more strongly than they attract adjacent sheets, with the consequence that if a montmorillonite suspension is carefully dried so that all the individual sheets lie parallel to one another, then as water vapour is added, the water molecules penetrate between the sheets, causing them to swell. At low relative humidities only one layer of water molecules enter, and they appear to be arranged in hexagonal packing if the cation present is lithium, magnesium or calcium, each lithium ion having three and each magnesium and calcium ion having six water molecules around it; but in sodium, potassium and acid-washed clays and in clays with other exchangeable cations of low surface density of charge, the water molecules do not take up regular positions between the layers. At higher humidities more water layers can be formed between the sheets, but the arrangement of the molecules, the actual spacings between the sheets, and possibly even the relative orientation of the sheets become so irregular that they cease to give proper X-ray photographs.[1] Montmorillonite particles, therefore, if properly dispersed in water, consist of flakes of individual oxygen sheets, and their size is found to be 100–150 Å. in diameter and 10 Å. in thickness.[2] In so far as larger particles are found, this is due solely to inefficient dispersion of the individual flakes, and the apparent size distribution of a montmorillonitic clay depends solely on the method of dispersion used and not on the clay.[3] These individual flakes can only be resolved in electron microscopic photographs if special techniques are used. R. K. Schofield[4] has been able to confirm this conclusion from experiments on the negative adsorption of anions in dilute sodium and calcium bentonite suspensions, for these results show that these particles must have a surface area of about 800 sq. m. per gm., which is equivalent to sheets 10 Å. thick.

Water is not unique in being able to penetrate between adjacent montmorillonite sheets; all polar liquids, and in particular all those with hydroxyl groups have this property. Some, such as glycerol and the glycols, can replace water from between these sheets and allow the adjacent sheets to have a spacing that is sufficiently constant and characteristic to be used as a diagnostic feature for identification.[5] This property of water and alcohols to interpenetrate between clay

[1] S. B. Hendricks, R. A. Nelson and L. T. Alexander, *J. Amer. Chem. Soc.*, 1940, **62**, 1457.
[2] N. Hast, *Nature*, 1947, **159**, 354.
[3] B. T. Shaw (*J. Phys. Chem.*, 1942, **46**, 1032) was able to show the validity of this statement, using the electron microscope.
[4] *Nature*, 1947, **160**, 407.
[5] D. M. C. MacEwan, *Nature*, 1944, **154**, 577; *J. Soc. Chem. Indust.*, 1946, **65**, 298; W. F. Bradley, *J. Amer. Chem. Soc.*, 1945, **67**, 975.

mineral sheets is not confined to montmorillonite; halloysite, which is also composed of randomly stacked sheets having no definite bonding forces between them, acts in a similar way.[1]

Two other minerals have recently been recognised in the clay fraction of some soils—vermiculite and chlorite, both of which are layer lattice minerals. Vermiculite probably has a structure similar to montmorillonite,[2] and possesses a very considerable base exchange capacity, perhaps as high or higher than montmorillonite, and shows the same phenomena of lattice spacing depending on water content, whilst chlorite probably has a much lower base exchange capacity. Probably neither mineral is as stable in the soil as kaolinite, and in fact they are probably intermediate products in the conversion of micas into kaolinite. G. F. Walker[3] has found vermiculite and D. M. C. MacEwan[4] has found both chlorite and vermiculite in a number of Scottish soils.

The shape of the clay mineral particles depends on their crystal structure. The clay minerals found in soils are plate-like, and their size depends on the binding forces present between adjacent sheets. The stronger the forces, the larger in general are the clay particles. Thus kaolinites tend to have larger particles than illites, because adjacent sheets, when regularly arranged, are held together by hydrogen bonding, which is stronger than the potassium bonding in illites, due perhaps to the fewer potassium bonds present. Again montmorillonites have the smallest particles because of the absence of forces to hold adjacent sheets together. Thus, as can be seen in Plate IV,[5] many kaolinite particles can easily be resolved in the electron microscope and be seen to have sharp edges, whilst montmorillonite particles are too small to be resolved at the magnifications used, though they now can be with some modern techniques.

[1] D. M. C. MacEwan, *Nature*, 1946, **157**, 159.
[2] J. W. Gruner, *Amer. Min.*, 1934, **19**, 557; I. Barshad, ibid., 1948, **33**, 655.
[3] *Min. Mag.*, 1950, **29**, 72.
[4] *Verre et Silic. Industr.* (Brussels), 1948, **13**, 41.
[5] For other photographs of clay minerals taken with the electron microscope, see B. T. Shaw, *J. Phys. Chem.*, 1942, **46**, 1032; C. E. Marshall *et al.*, *Soil Sci.*, 1942, **54**, 149; *Proc. Soil Sci. Soc. Amer.*, 1942, **6**, 146; 1943, **7**, 58.

CHAPTER VII

THE CATION- AND ANION-HOLDING POWERS OF SOILS

Soils have been known to hold cations ever since J. T. Way established the existence of base exchange a century ago, but the mechanism by which these bases are held has been the subject of long controversies. Two descriptions of this mechanism were suggested. It was discovered that soils could be acid, that this acid was insoluble and due to the mineral particles of the soil, and that the clay fraction was the main seat of this acidity. On the other hand, it was discovered that soils could absorb alkali, and that this absorption did not appear to be accompanied by any base exchange. Hence, a second school of thought considered that this was as important a mechanism as the mere neutralisation of acidity.

The methods used for investigating the insoluble soil acids were taken over from the methods developed by physical chemists for estimating the strength of weak soluble acids, as, for example, acetic. The principal method employed was to determine the buffer curve of the acid soil, which was done by making a suspension and measuring its change of *p*H as increasing quantities of an alkali were added; for the soil is a buffer, that is, it reduces the rise in *p*H that would occur if the alkali was added to a volume of water equal to that of the soil suspension. Fig. 5 gives an example of a buffer curve of a weak polybasic acid, and Fig. 6 shows that for a clay; but it also shows that the curve depends very strongly on both the base used and the concentration of salt present, and that it has no sharp end-point. One can also show that the actual shape of the curved part of the curve differs from that of a weak acid. Many soil chemists have assumed that clay really is a weak polybasic acid and have tried to find reasons for the differences between the buffer curves of clay and of the soluble weak polybasic acids.

Our present knowledge of the constitution of clays has, however, rendered most of this discussion obsolete, for clays possess a negative charge in addition to any true acidic groups they may have. Further techniques have now been developed that will eliminate many uncontrolled factors that are responsible for some of the features of the curves shown in Fig. 6, so that one can obtain buffer curves that can be more precisely interpreted.

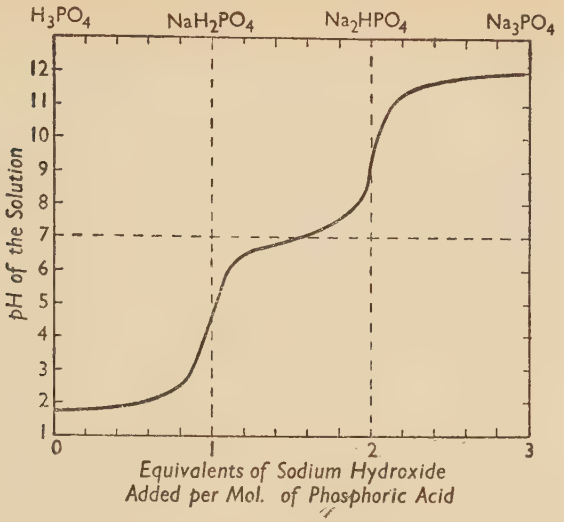


FIG. 5. Titration curve of phosphoric acid with sodium hydroxide.

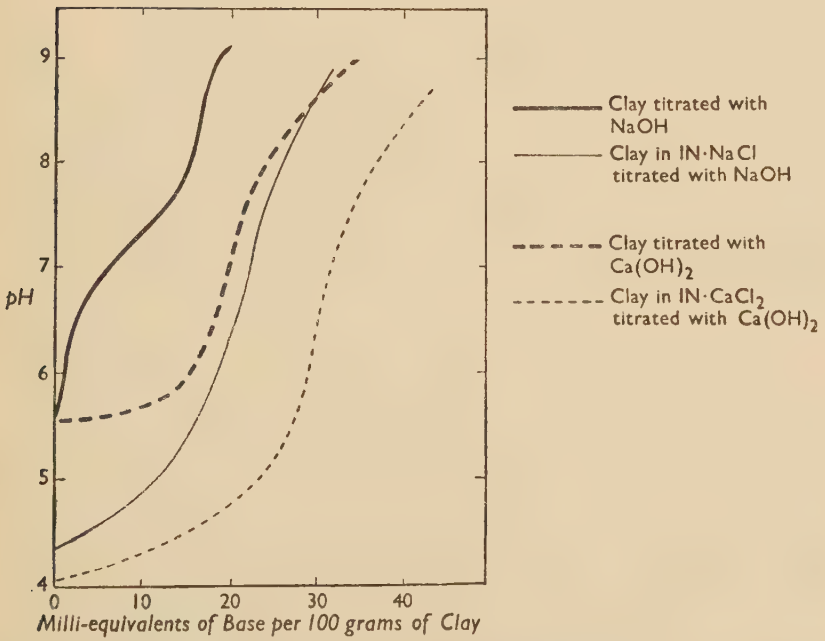

pH
Milli-equivalents of Base per 100 grams of Clay
Clay titrated with NaOH
Clay in IN·NaCl titrated with NaOH
Clay titrated with $Ca(OH)_2$
Clay in IN·$CaCl_2$ titrated with $Ca(OH)_2$

FIG. 6. Titration curve of a clay separated from a Bengal soil, showing the effect of the base used and the salt concentration.[1]

[1] Taken from J. N. Mukherjee and R. P. Mitra *Indian J. Agric. Sci.*, 1942, **12**, 433.

The Cation-holding Power of Clay Minerals

R. K. Schofield has devised techniques for measuring the electric charges carried by clay particles. Pure clay minerals have a net negative charge which must be neutralised by cations; and these charges have two separate origins. The clay particles have a negative charge due to isomorphous replacement in the lattice, and they develop a negative charge due to the dissociation of hydrogen ions into the surrounding water from hydroxyl groups situated at the edges of the crystal lattice. If adequate steps are taken to secure complete exchange of cations, Schofield showed that between *p*H 2·5 and *p*H 5 the negative charge is constant, and this charge presumably represents the permanent charge on the clay lattice due to isomorphous replacement. At *p*H 6, dissociation of hydrogen ions from hydroxyls is still very small, but becomes appreciable at *p*H 7. The hydroxyls that liberate these hydrogen atoms are probably situated along the edges of the tetrahedral oxygen sheet, for the outside oxygen atoms of this sheet can only be in contact with one and not two silicons, and hence each takes on a hydrogen ion to neutralise its surplus charge. The hydrogens of octahedral hydroxyls attached to the aluminium ions are probably unable to dissociate in this *p*H range.

Hence the cation-holding power of clay minerals falls into two parts: in the range 2·5 to 5, they hold a definite amount of cation, enough to neutralise the charge due to isomorphous replacement; and in the range above 6, they hold in addition enough bases to neutralise the weak acid produced by hydrogens dissociating from certain hydroxyls. Fig. 7 gives one of Schofield's curves for montmorillonite; and his figures for the milli-equivalent of base held by 100 gm. of montmorillonite and kaolinite in two *p*H ranges are:

	*p*H 2·5–*p*H 6	At *p*H 7	Due to dissociation of hydroxyls at *p*H 7
Kaolinite . . .	4	10	6
Montmorillonite . .	95	100	5

This shows that the number of dissociable hydrogen ions between *p*H 6 and *p*H 7 from kaolinite and montmorillonite are of the same order of magnitude though the permanent charge of the montmorillonite is about twenty times greater.[1] Rothamsted subsoil behaves very similar to these clay minerals, as can be seen from Table 28 on p. 114. Thus, when in equilibrium with *N*/5 ammonium chloride it holds

[1] For another series of experiments showing this relative difference between kaolinite and montmorillonite above *p*H 6, see I. F. Radu, *Bodenk. PflErnähr.*, 1940, **21**, 574.

27 milli-equivalents per 100 gm. of ammonium ions at *p*H 7 and has a negative charge of 23 milli-equivalents at *p*H 2·5; and most of this 4 milli-equivalents difference occurs between *p*H 6 and *p*H 7.

If this picture is correct, one can understand the result found by several workers that the base exchange capacity of kaolinite, that is, the total bases it can hold in some rather ill-defined *p*H region around neutrality, increases as its particles become smaller,[1] whereas this effect is far less noticeable, in proportion, with montmorillonite.[2] For the smaller the particles the greater is the total number of hydroxyls

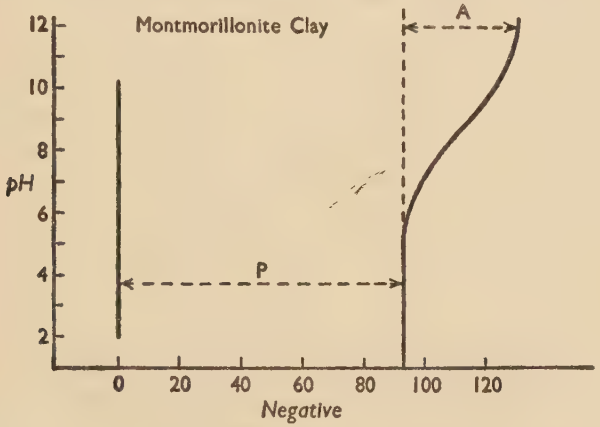


FIG. 7. The titration curve of a montmorillonite clay.

P is the permanent negative charge on the clay.
A is the additional negative charge developed at high *p*H.

attached to silicons, and this is a major cause of base holding power in kaolinite, but only a minor cause in montmorillonite.

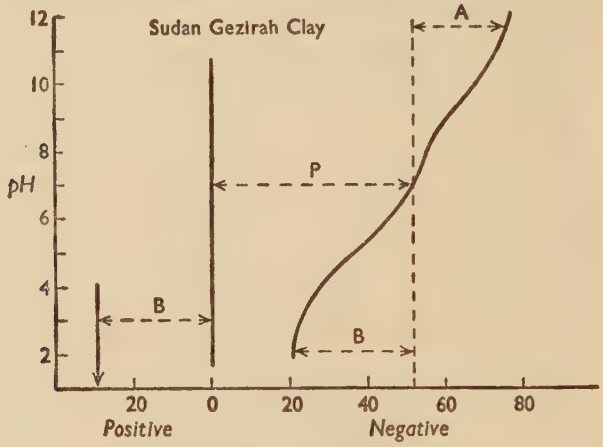
The Clay Acid

Soil clays do not necessarily give the same shaped buffer curve as montmorillonite even when this elaborate technique is used. Fig. 8 gives the comparable curve for a clay soil taken from the Sudan Gezirah, whilst Fig. 7 was for montmorillonite in the mineral bentonite. The soil contains besides clay some non-crystalline inorganic components, as described on p. 79, which in acid solution acquire a positive charge by dissociating hydroxyls; hence provided the negative charge

[1] A. L. Johnson and W. G. Lawrence, *J. Amer. Ceram. Soc.*, 1942, **25**, 344.

[2] E. A. Hauser and C. E. Reed, *J. Phys. Chem.*, 1937, **41**, 911. For soil clays behaving like montmorillonite, see D. M. Whitt and L. D. Baver, *J. Amer. Soc. Agron.*, 1937, **29**, 905 (Putnam Clay), and for one behaving more like kaolinite, C. E. Marshall, *Ztschr. Kryst.* 1935, **91**, 433 (Rothamsted Clay).

on the clay surface remains constant, the net negative charge on the mixture of clay and these constituents falls as the *p*H falls, as will be shown in Table 28 on p. 114. In fact, for the Rothamsted soil, the true negative charge does in fact remain constant below *p*H 5, and the apparent decrease is entirely due to the positive charge developed. And this is true also for the Sudan soil in Fig. 8, for the greater part of the curve to the left of the dotted vertical line is due to the increasing number of positive charges being developed. It is also shown on p. 114



Charge in Milli-equivalents per 100 grams of Soil.

FIG. 8. The titration curve of a heavy alluvial clay soil.

P is the permanent negative charge on the clay.
A is the additional negative charge developed at high *p*H.
B is the positive charge developed at low *p*H.
The arrow shows the maximum uptake of chloride from alcoholic HCl.

that if the material giving these positive charges is removed, by treating the soil with Tamm's acid oxalate reagent, then the buffer curve takes the same shape as that of montmorillonite in Fig. 7.

But buffer curves such as those given in Fig. 6 are dependent on still another factor that was purposely eliminated from those given in Figs. 7 and 8, and to understand what this is, one must consider in more detail what are the exchangeable bases on an acid soil or clay.

Acid soils have long been known to contain readily displaceable aluminium, for if an acid soil is leached with a neutral salt a considerable but definite quantity of aluminium compounds are found to have been leached out. Again, the buffer curve of an acid soil has been shown by Schofield to be dependent on aluminium, as is illustrated in Fig. 9. The heavy full curve on the left is for an unmanured plot in the Rothamsted Park Grass, that on the right is for a neighbouring

plot which has received eighty annual dressings of 600 lb. sulphate of ammonia per acre. After treatment with aluminium chloride the unmanured soil gave the dotted curve, and its resemblance to the curve for the sulphate of ammonia plot provides striking support to H. Paver and C. E. Marshall's[1] view that in acid soils aluminium acts as an exchangeable base. On the other hand, soil from the sulphate of ammonia plot treated first with dilute hydrochloric acid and then with

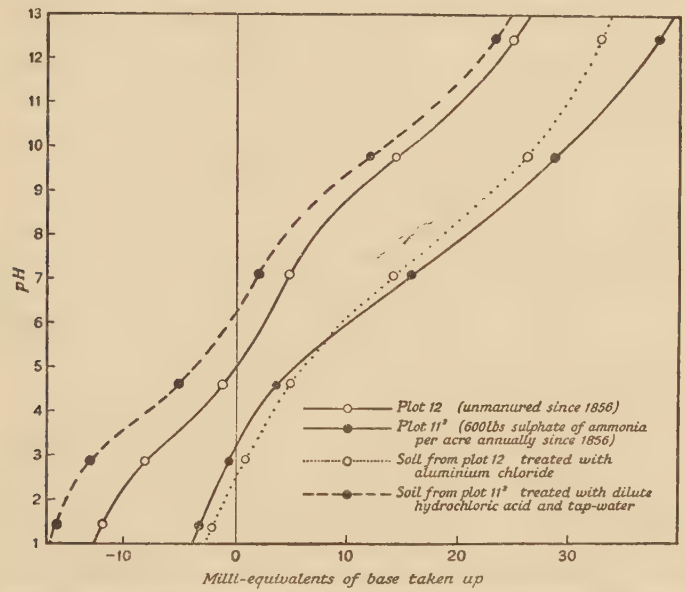


Fig. 9. Influence of aluminium on the buffer curve of Rothamsted soil (R. K. Schofield).

a gentle stream of hard water for several days, gave a curve so like that of the unmanured soil as to suggest that calcium had displaced the aluminium ions. The aluminium liberated when acid soils are leached with neutral salt solutions contributes largely to the so-called "exchange acidity" determined by titrating the leachate to a neutral or alkaline end-point.

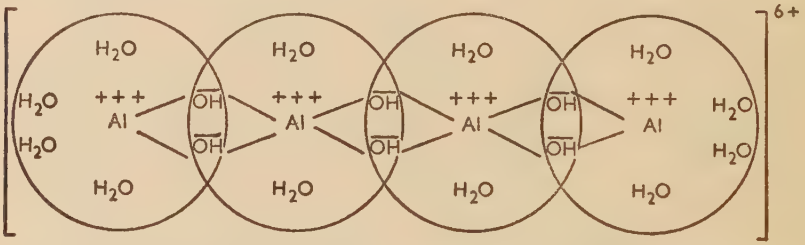
The detailed processes by which aluminium gives these buffering effects has not yet been definitely settled, but Schofield[2] has suggested the following mechanism. Under very acid conditions, when the *p*H is below 4, the aluminium is present as single aluminium ions, each of which carry three positive charges, and is surrounded by six water molecules in 6-co-ordination. As the *p*H rises by the addition of a base, which naturally gives rise to hydroxyl ions in the suspension,

[1] *J. Soc. Chem. Indust.*, 1934, **53**, 750. [2] *Soils and Fert.*, 1946, **9**, 265.

hydrogen ions dissociate from one or two of the water molecules surrounding the aluminium to neutralise these added hydroxyls, and in consequence leave one or two hydroxyl ions around the aluminium. This unit appears to be unstable and combines with another like unit by sharing two hydroxyls and losing two water molecules, but the unit now only carries four positive charges in all, instead of six, thus allowing some of the cations of the added base to neutralise some of the permanent negative charge on the clay. This process can be represented thus:

$$2Al(H_2O)_6^{3+} + 2OH^- \rightarrow [Al_2(OH)_2(H_2O)_8]^{4+} + 4H_2O.$$

As the *p*H continues to rise, so more hydrogen ions (or hydrions for short) dissociate from the co-ordinated water molecules of these units, giving units such as the following:



Once the *p*H has risen above 5, these units have joined together, and are precipitated as aluminium hydroxide $Al(OH)_3$. This hydroxide remains stable until *p*H 9, when it breaks up into aluminium ions in 4-co-ordination with hydroxyls giving the aluminate anion $Al(OH)_4^-$.

This transition from aluminium ions in 6-co-ordination with water into insoluble aluminium hydroxide in the form of gibbsite, in which the aluminium ions still remain in 6-co-ordination with hydroxyl ions, takes place in the *p*H range 4–5 in solution, but in soils it will appear to take place at higher *p*Hs. For the *p*H of a soil is commonly measured when it is dispersed in water, and as will be explained on p. 99, this has the consequence that the hydrogen-ion concentration on the clay surface is considerably higher, usually by about one *p*H unit lower, than that in the solution. Hence this transition covers the *p*H range of 5–6 in soils when the *p*H is measured in a water suspension.

Aluminium appears to be the only element in the soil that can play this role. With iron, for example, ferric hydroxide is formed at *p*H 2·5, which is so much lower than for aluminium that the transition from ferric ions to ferric hydroxide occurs in a *p*H range beyond that found in any but exceptionally acid soils. Aluminium, in fact, is usually the only cation that neutral salts wash out of acid soils in appreciable quantities.

The weight of evidence at the present time is therefore that acid mineral soils and clays are aluminium and not hydrogen soils. Thus in the first place, the clay lattice is unstable if the only cations available to neutralise its permanent negative charge are hydrogen: it breaks up to release sufficient tetrahedral or octahedral aluminium, or other cations, to neutralise the permanent charge. It is for this reason that acid-washed or electro-dialysed clays and mineral soils can never have a very low *p*H when suspended in water—it is always higher than 4 and may be above 5, and it is known as the ultimate *p*H of that soil. In the second place, as has already been shown, a mineral soil or clay suspended in an acid salt solution containing a cation in a suitable concentration, which was ammonium in $N/5$ concentration in the example given in Table 28 on p. 114, has practically none of its negative charge neutralised by hydrogen ions in the *p*H range 2·5 to 5. As one would expect, the neutralising cation is in a much higher concentration than the hydrogen in the double layer. It is only when the *p*H falls below 2·5, or the hydrogen-ion concentration rises above $N/300$, that its concentration is sufficient for it to be present in the double layer in comparable concentration to the other cations, but the solution has become so acid that the clay lattice is becoming unstable.

A clay, therefore, does not have any true buffer capacity nor any true acidic groups at *p*Hs below that at which hydroxyls attached to silicon ions at the broken edges of the clay lattice begin to dissociate hydrogen ions, that is below *p*H 5–6. One can therefore talk legitimately about acid soils and acid clays, but not about clay acids, nor is it correct to call acid clays hydrogen clays.

Humic material differs completely from clay in this respect; for humic acids contain carboxylic groups —COOH which will dissociate hydrogen ions in acid conditions. They are therefore true weak acids, as can be seen from the typical titration curve given in Fig. 20 on p. 262. Surface soils containing organic matter do therefore have some true acids present as well as negatively charged surfaces.

Three separate mechanisms affecting the buffer curves of clays have so far been recognised and their effects isolated: the permanent charge on the lattice due to isomorphous replacement, the dissociation of hydrogen ions from hydroxyls situated on the edge of the crystal lattice and joined to silicon atoms, and the presence of hydrated aluminium cations from which hydrogen ions can dissociate from the water molecules. These may not exhaust the mechanisms present in clays, as there is still one more phenomenon found in buffer curves that has not been fully explained. If an acid clay is being titrated with a hydroxide, the clay shows an abnormal uptake of the cation at *p*Hs just below that of the saturated solution of the hydroxide, or, if the hydroxide is

completely insoluble, that at which the hydroxide is formed. This behaviour is shown equally by cations such as calcium and barium, which do not form basic salts, as by cations such as magnesium, manganese, nickel and zinc, which do.[1]

The limitation of the concept of the base exchange capacity of a clay can now be appreciated. This concept originally assumed that there was a definite amount of acidity, or of exchangeable hydrogen on an acid clay, and that the amount of base required to neutralise this represented its base exchange capacity. It was soon found that this concept could not be defined in such a way that it could be measured. It was, therefore, given an arbitrary definition, which varied from worker to worker, such as the amount of base the acid clay could take up from a standard barium hydroxide or lime-water solution, or from a given salt solution, or from a salt solution at a given *p*H. It can now be appreciated that, unless one chooses to define the base exchange capacity of a clay as the permanent negative charge carried by its particles, it can only have an arbitrary meaning, such as the amount of base the clay holds at *p*H 7 under specified conditions.

The *p*H of a Soil

The *p*H of an aqueous solution is defined as the negative logarithm of the hydrogen-ion concentration in the solution, and as the individual molecules and ions composing the solution are uniformly dispersed throughout it within the limits set by variations due to molecular and ionic thermal movements, the concept is perfectly definite so long as one is dealing with volumes large compared with molecular dimensions. These volumes may however have to be very large, in terms of molecular dimensions, at the end of the *p*H range of importance in soils. Thus a solution at *p*H 7 will, on the average, contain one hydrogen ion in a cube of side 0·25 μ—just about the minimum sized volume visible fairly clearly in a microscope fitted with a $\frac{1}{12}$ in. objective. But the *p*H of a soil dispersed in water is not a simple concept like this; for the soil particles, which carry ions attached to them, are very large compared to molecular dimensions, and the ions are, therefore, not uniformly distributed throughout the solution. The concept of the *p*H of a soil, or rather a soil suspension, is, therefore, complex, and it can only be discussed in relation to some properties of the ionic atmosphere around the soil particles. The ionic atmosphere around a charged particle will be discussed on p. 125, but the following explanation is required in the present context.

Consider a negatively charged soil particle surrounded by water.

[1] C. A. Bower and E. Truog, *Proc. Soil Sci. Soc. Amer.*, 1940, **5**, 86.

The negative charge is neutralised by cations, but these cations do not necessarily sit firmly on the negative charges: a proportion dissociate into the dispersion medium. Thus as one goes from the surface of the clay surface outwards, the concentration of cations gradually decreases until it becomes very small. This diffuse layer of cations is known as the diffuse double layer—a double layer because there is a negative charge on the clay surface which is balanced by this diffuse cloud of positive charges; and the thickness of this layer is measured by the distance one must go from the surface until the cation concentration becomes inappreciable. But soils are never bathed in pure water; there are always some salts dissolved in the water. One effect of these salts is that their cations intermingle with the exchangeable cations in the double layer and make it less diffuse or more compact: in fact they reduce the difference in cationic concentration between the neighbourhood of the clay surface and the bulk of the solution. The more concentrated the salt and the higher the valency of the cation, the thinner the double layer and the more nearly is the cation concentration on the clay surface the same as in the solution away from the clay surface; and this holds for every species of cation in the double layer.

This effect of salts is directly relevant to the limitations inherent in the concept of the *p*H of a soil. The hydrogen-ion concentration in the solution surrounding the soil particles is less than that on the soil particles themselves, due to the hydrogen-ion concentration gradient in the double layer. But as the double layer is made more compact as, for example, by adding an electrolyte to the soil-water system, so the hydrogen-ion concentration gradient across the double layer is reduced and the *p*H in the solution becomes nearer to that on the surface of the soil particle. The *p*H of the solution is thus greater than the *p*H of the particle surface, and if the *p*H of the particle surface remains constant, the *p*H of the solution will decrease as it becomes more concentrated. This effect of salt concentration on *p*H is well known in the laboratory, and is the reason why some workers measure the *p*H of a soil in a solution of normal potassium chloride rather than in water. For in such a solution the double layer is very compact and the hydrogen-ion concentration on the soil surface is only a little larger than that in the solution. But this *p*H is often a whole *p*H unit lower than that found when the soil is shaken up in water.

These results help to explain the observed fact that the *p*H of a soil, as measured by shaking it up in water, varies considerably during the growing season,[1] for the amount of salts in the soil solution depends on such factors as the rate of oxidation of the organic matter, the rate of

[1] For examples, see A. M. Smith and J. M. Robertson, *J. Agric. Sci.*, 1931, **21**, 822; J. D. Hartman, *Proc. Soil Sci. Soc. Amer.*, 1938, **3**, 138.

uptake of ions by the plant and their rate of leaching from the soil. But the concentration of the soil solution is also varying continuously depending not only on the amount of salts present but also on the moisture content of the soil. Obviously as the soil gets drier so the concentration of the soil solution rises and its *p*H will fall, as is shown in Table 25 for three Arizona soils.[1] It is possible this is one of the reasons why crops sensitive to soil acidity appear to tolerate greater acidities in moist than in dry climates, because for a given soil *p*H as measured by shaking up in water, the acidity of the soil solution will rise as the soil becomes drier, and the root system of the crop may suffer accordingly.

TABLE 25

The Effect of Soil-Water Ratio on the Soil's pH

Calcareous alkaline soils from Arizona

Volume of water added per 100 gm. dry soil	*p*H of soil suspension or paste		
	Soil 1	Soil 2	Soil 3
10 c.cm. . . .	7·45	9·10	7·95
25 c.cm. . . .	7·60	9·40	8·00
100 c.cm. . . .	7·70	9·85	8·20
1000 c.cm. . . .	8·15	9·90	9·20

The *p*H of a soil is influenced by two other factors besides the *p*H rise from the surface of the soil particles to the soil solution in bulk. In the first place, soils may contain substances capable of changing their degree of oxidation and reduction, with consequent fall or rise in *p*H. Thus water-logged soils are commonly nearly neutral and have some sulphides present. If such a soil is drained the sulphides become oxidised to sulphates and the *p*H may fall from 7 to 4 or below. And if a sample of such a water-logged soil is taken, and allowed to air-dry slowly before its *p*H is determined, the *p*H may fall strongly, whilst if the soil is left water-logged its *p*H will rise slowly.[2] It is possible also that manganese ions in particular, and other metallic ions which can change their valency in the soil with changes in aeration, will also contribute to fluctuations in *p*H, raising the *p*H as their valency is reduced, and lowering it, that is, increasing the soil acidity, as it is increased.

[1] W. T. McGeorge, *J. Amer. Soc. Agron.*, 1937, **29**, 841. For further examples, see M. R. Huberty and A. R. C. Haas, *Soil Sci.*, 1940, **49**, 455, and 1941, **51**, 17; L. E. Davis, *Soil Sci.*, 1943, **56**, 405.

[2] For examples of this effect, see M. Romanoff, *J. Res. Natl. Bur. Stand.*, 1945, **34**, 227; *Gas*, 1945, **26**, 49.

The *p*H of a soil is also influenced by the carbon dioxide concentration in the soil air. The higher this concentration the lower the *p*H, and the *p*H of a neutral soil is most sensitive to small changes in the carbon dioxide concentration when the concentration itself is low, that is, when it is not very different from the atmospheric value of 0·03 per cent. R. S. Whitney and R. Gardner[1] have given examples of this effect for a number of neutral and alkaline soils, and found that the reduction of *p*H was proportional to the logarithm of the carbon dioxide pressure, and that the effect was larger the higher the soil's *p*H. The magnitude of this effect can be calculated approximately for a calcareous soil, that is, a soil containing free calcium carbonate, for the system being examined is fundamentally calcium carbonate—calcium bicarbonate—carbon dioxide—water, and the *p*H of this system depends mainly on the relative concentrations of calcium and bicarbonate ions in the solution. Table 26 gives the *p*H of this system in the absence and in

TABLE 26

The pH of Calcium Carbonate and Calcareous Clay Suspensions in Equilibrium with Carbon Dioxide at Varying Pressures

Carbon dioxide pressure in atm.	pH of		Calcium held by the clay milli-equiv. per 100 gm.
	$CaCO_3$ system	Clay–$CaCO_3$ system	
0·00033	8·42	8·57	71·3
0·00295	7·66	7·97	62·4
0·00467	7·54	7·87	59·3
0·00999	7·32	7·67	49·7
0·02130	7·21	7·57	43·0
0·03010	7·07	7·28	37·9
0·05000	6·91	7·19	26·4

the presence of a separated clay when in equilibrium.[2] In this particular example the separated clay raised the *p*H of the system slightly, which does not usually happen in calcareous soils. It also shows that as the CO_2 concentration rises, so the clay gives off more exchangeable calcium to the soil solution, and this equally applies to the other exchangeable ions in soils.

The *p*H of a calcareous soil containing little exchangeable sodium or magnesium ions cannot exceed about 8·5 when in equilibrium with the atmosphere, but if the CO_2 concentration rises to 0·1 per cent, a low figure for most soils, the *p*H has already dropped to 8, and if it rises to

[1] *Soil Sci.*, 1943, **55**, 127; **56**, 63. [2] F. Simmons, *J. Amer. Soc. Agron.*, 1939, **31**, 638.

1 per cent, a common figure for pastures, the *p*H is under 7·5. Now, as will be shown later (p. 478), many plants suffer from phosphate and minor element deficiencies if the *p*H rises much above 8, and hence they can only thrive on calcareous soils if they can maintain an adequate concentration of carbon dioxide around their roots. This is more easily achieved in soils of low porosity, such as clays, than in soils of high porosity, such as well drained sands, and in soils rich in organic matter than in poor, and in soils under pasture than under arable.

Soils can only have a *p*H over 8·5 if they contain enough exchangeable sodium for sodium carbonate to be present in the soil solution. These soils are known as alkali soils and are discussed on p. 545, but Whitney and Gardner showed that even if their *p*H is above 9·5, when measured in equilibrium with the atmosphere, it may be below 8 when in equilibrium with air containing 1 per cent of CO_2. Hence, in calcareous and alkali soils the effective *p*H for as far as the plant roots are concerned can be considerably lower than the *p*H determined by shaking up in water because of the greater concentration of carbon dioxide the roots can maintain in their immediate neighbourhood, and this effect can be still further increased due to the electrolyte concentration in the solution.

Soils do not normally have *p*Hs below about 4·5 to 4 unless they contain free acids such as sulphuric; and this limit is set by the behaviour of the complex hydrated aluminium ions in the soil solution. For, as already explained, soils containing appreciable amounts of replaceable hydrogen appear to be unstable and decompose to release sufficient aluminium to neutralise the greater proportion of the net negative charge on the mineral soil particles.

SUMMARY OF THE FACTORS AFFECTING THE *p*H OF A SOIL

This discussion has brought out the following factors:

1. The electric double layer surrounding the particles showing base exchange causes the hydrogen-ion concentration on the outside of the double layer to be less than that on the surface of the particles. This reduction in the hydrogen-ion concentration is greater the more dilute the solution surrounding the particles. Thus, the *p*H of the solution depends on the ionic concentrations present in it.

2. If the soil contains any substances capable of changing their state of oxidation or reduction, such changes of state alter the *p*H of the soil.

3. The *p*H of a soil depends on the carbon dioxide concentration in the soil air, and this effect is more important at a high than a low *p*H.

Thus the *p*H of a soil has no clearly defined unique value, but depends on the conditions of measurement, which, in the field, may

cause variations of nearly one unit. Hence, for general advisory purposes there is no justification in measuring it to an accuracy greater than 0·2 unit, and probably to one greater than 0·5 unit.

The Lime Requirement of a Soil

The *p*H of a field soil is only one of the properties of an acid soil of importance to the farmer; he also wants to know how much lime, that is, calcium carbonate or other liming material, he should put on

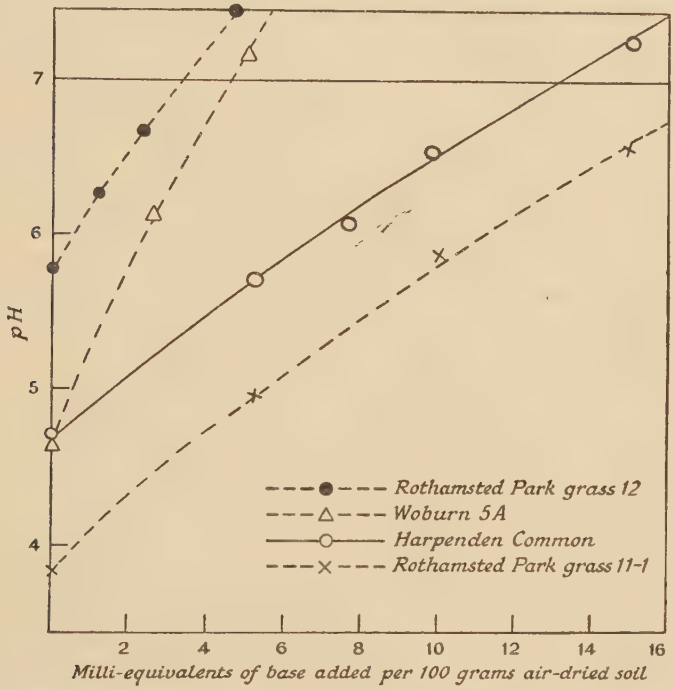


FIG. 10. Changes in reaction (*p*H) of acid soils with successive additions of lime-water.[1]

the soil to neutralise its acidity, or at least to neutralise it sufficiently for good crop growth. The effect of *p*H as such on crops and plants will be discussed in Chapter 27; but here we are only concerned with the amount of lime needed to bring the soil to a given *p*H, without justifying the *p*H chosen.

There is obviously no simple relation between the *p*H of an acid soil and the amount of lime that must be added to bring about any particular change in its *p*H, as can be seen from Fig. 10, which shows the titration or buffer curves for four soils, two of which, the Harpenden Common and the Woburn soil, have the same initial *p*H, but need very different

[1] E. M. Crowther and W. S. Martin, *J. Agric. Sci.*, 1925, **15**, 237.

quantities of lime to give an equal change in their *p*H due to their very different clay contents.

A knowledge of the buffer curves as determined by doing this electrometric titration of the soil with lime in the laboratory does not, in fact, allow of a good prediction of the amount of lime needed in the field to give a selected increase in the soil's *p*H. This is illustrated by some results of H. R. Christensen and S. Tovborg Jensen[1] for two Danish soils, in Fig. 11. They converted their laboratory results into hypothetical field results by assuming the added lime, in the form of calcium

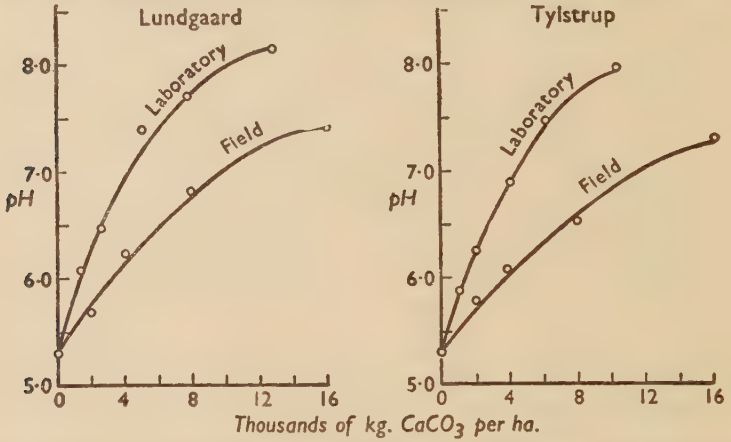


FIG. 11. Influence of successive additions of $CaCo_3$ on the *p*H values of two acid soils in the laboratory and the field respectively.

carbonate, was distributed and completely absorbed throughout the top 20 cm. of soil, which weighed 2·4 million kg. per hectare. Fig. 11 shows that the soil in the field appears to need two to three times as much lime to bring its *p*H up to a selected value than is indicated by the laboratory titration curve, and this factor is sometimes known as the liming factor. R. L. Mitchell[2] found a similar factor for four out of five Scottish soils, although the fifth soil gave a factor nearer to unity. O. de Vries and P. Bruin[3] found many Dutch soils had a liming factor of 2 and about one-third had one of 3, and L. E. Dunn[4] found some medium to heavy soils in western Washington had liming factors under 2.

For estimating the lime requirement, the whole titration curve of the soil is not required; it is sufficient to determine the amount of lime needed to bring it to a selected *p*H. This can be done either by titrating

[1] *Trans. 2nd Comm. Int. Soc. Soil Sci.*, Groningen, 1926, A, p. 94.
[2] *J. Agric. Sci.*, 1936, **26**, 664. See L. A. Whelan, ibid., 1939, **29**, 306, for a continuation of this data.
[3] *Emp. J. Expt. Agric.*, 1947, **15**, 260.
[4] *Soil Sci.*, 1943, **56**, 341.

the soil with lime to this *p*H, or, more conveniently, by shaking the soil with a calcium solution buffered at this *p*H. In advisory work, the method used usually brings the soil to a *p*H well above *p*H 6·5 in the laboratory,[1] and when the dressing of calcium carbonate, based on this estimation, is given to the soil in the field it usually brings it to about this *p*H, presumably because most soils have an appreciable liming factor. Again, in advisory practice no great accuracy is expected for this determination, for on medium to heavy soils over-liming causes no troubles, and the extra calcium carbonate acts as a calcium reserve, whilst on some sandy and peaty soils even the proper lime requirement often cannot be given at a single dressing, for such a dressing of calcium carbonate may induce trace element deficiency troubles in the crop (p. 480). Here the lime must be given in small frequent dressings and, in fact, the correct amount is found by a continual check on *p*H or crop performance whenever additional dressings of lime are given. The problem is often eased by the fact that applying only half the lime requirement to many light soils allows most crops to give almost as large a yield as when the full lime requirement is given. This again emphasises the very great latitude one has in the actual dressing of lime to be applied to any soils except those very sensitive to over-liming; and it also emphasises the vagueness of the concept of lime requirement—it is a useful working concept that can have no exact meaning.

Some confusion has been caused by the use of the word "lime" for the material added to the soil to neutralise soil acidity. At the present time, lime usually refers to calcium oxide, also called burnt or quicklime, or to calcium hydroxide, also called hydrated or slacked lime; but in the past it also included calcium carbonate, as can be seen in the word limestone. There is no accepted word for a material that neutralises soil acidity, which must include not only these compounds but also some slags and other forms of calcium silicate, and the phrase "liming material" must often be used. The question arises whether any particular form of liming material is better than any other, and in particular if there is any object in using fuel to burn limestone or chalk to convert it into the oxide or hydroxide. There used to be an advantage because it was once the easiest way to convert the rock into a powder, but crushing machinery is now available for grinding limestones to any degree of fineness. Finely-divided calcium oxide and hydroxide when mixed with the soil are rapidly converted into the carbonate and though it is possible that either may neutralise soil acidity rather faster than finely-ground carbonate, there seems to be no

[1] For a comparison of several methods in use, see R. F. Innes and H. F. Birch, *J. Agric. Soc.*, 1945, **35**, 236; S. K. Mukherjee *et al.*, *Indian J. Agric. Sci.*, 1944, **14**, 74, 203.

field evidence that this is of any practical consequence if the liming material is applied one or two months before the crop is planted, and in fact the long-term effect of all liming materials on other soil properties, such as the level of the soil organic matter, appears to be independent of whether calcium oxide or carbonate is used.[1]

The calcium carbonate must, however, be crushed if it is to become available fairly quickly in the soil. If it is chalk, crushing to a fine powder is technically simple, although the chalk may have to be dried beforehand. If the carbonate is a limestone rock, the coarser the material can be ground, the cheaper will be the process. Limestone crushed to pass a 10-mesh screen (aperture 2·0 mm.), but to be retained by a 30-mesh (aperture 0·59 mm.) takes longer to affect the *p*H of a soil than if it is crushed to pass a 100-mesh sieve (aperture 0·15 mm.), but twelve months after application the effects of the coarse and the fine are about equal, and for the next few years the residual effects of the coarse are rather higher than of the fine, as the fine washes out quicker in the drainage water.[2] Limestone coarser than 2 mm. is, however, an inefficient liming material. Now the process of crushing limestone rock produces fragments of many sizes, from fine dust upwards. Thus limestone crushed to pass a 10-mesh or a 20-mesh sieve may contain 25 per cent and 45 per cent of material that passes a 100-mesh sieve. Hence, this material, which is what the crushing mills naturally produce, is agriculturally preferable to material crushed and screened to a uniform size. Whether passing a 10-mesh or a 20-mesh sieve is the preferable upper limit of size has not been fully investigated, but for many limestones there appears to be little to choose between them; the important thing is to have a considerable variation in particle size in the material to ensure both rapid action initially and a reasonably long residual action.[3]

Now calcium bicarbonate is being continually washed out of the soil at an average annual rate equivalent to 2–4 cwt. of $CaCO_3$ per acre, as can be seen from the table on p. 502, but this rate depends on the amount and the solubility of calcium carbonate in the soil. Thus, W. Morley Davies[4] found that for a soil having a lime requirement of 40 cwt. per acre of $CaCO_3$ the average annual rate of loss by leaching was 1 cwt. per acre if 25 cwt. of $CaCO_3$ were added, 3 cwt. per acre if 50 cwt. $CaCO_3$ given, and 6 cwt. per acre if 100 cwt. were given.

[1] For the results of the Pennsylvania trials on this point, see J. W. White and F. J. Holben. *Soil Sci.*, 1924, **18**, 201.

[2] For American results, see W. H. Pierre, *Soil Sci.*, 1930, **29**, 137; T. L. Lyon, *Cornell Agric. Expt. Sta., Bull.* 531, 1931; W. H. MacIntire *et al.*, *J. Amer. Soc. Agron.*, 1933, **25**, 285; R. H. Walker and P. E. Brown, *Iowa Agric. Expt. Sta., Res. Bull.* 178, 1935. For New Zealand results, B. W. Doak, *N.Z. J. Sci. Tech.*, 1941, **23** A, 24.

[3] For an example, see W. A. Albrecht, *Soil Sci.*, 1946, **61**, 265.

[4] *Agric. Prog.*, 1938, **15**, 111.

P. Tuorila[1] has also found from the analyses of many Finnish liming experiments that the average annual loss of calcium carbonate from acid soils was roughly proportional to the dressings of calcium carbonate given, and that the effects of suitable dressings last for about eight to ten years, during which time between one-half and one-third of the calcium added has been lost in the drainage water. Hence, the present statutory compensation for the residual value of calcium carbonate allowed to outgoing tenants in England is based on the assumption that one-eighth of the carbonate is lost each year.

This rate of loss of carbonate probably depends on the fineness of grinding the limestone· the coarser the grinding, the smaller will be the loss in the first two to three years. But no figures appear to be available to show the magnitude of this effect.

Thus the present recommendations for liming an acid soil are that dressings higher than $3\frac{1}{2}$ tons per acre of $CaCO_3$ (equivalent to 40 cwt. per acre of CaO) are only justifiable under conditions of very high lime requirements, and that in general fairly small but frequent dressings are preferable to large but infrequent ones—the same advice as is now given for phosphatic fertilisers. However, some clay land farmers like to add much larger dressings of calcium carbonate per acre, but this is because they consider the calcium carbonate makes the tilth more friable and mellow (see p. 408), and has nothing to do with neutralising acidity.

The Relative Attractions of Clay for Different Cations

The negative charges on clay particles can be neutralised by any cation except hydrogen, and hence these charges must be accessible to very large cations. This is true for the charges between the layers of montmorillonite, for these can be neutralised by complex amines,[2] and proteins[3]—ions so large that the layers may be forced apart as far as 48 Å.; and the charge density on a montmorillonite surface is low enough, about one negative charge per 140 sq. Å.,[4] to take the largest cations so far used. This accessibility of the charged spots is a characteristic of clay minerals for neither natural zeolites nor artificial permutits show it; and it has the further consequence that, on the whole, base exchange equilibria in clays are reached very quickly.

Clays hold different ions, however, with different intensities. If samples of a clay saturated with calcium ions, for example, are shaken

[1] *Svenska Vall-o. MosskFören. Tidskr.*, 1945, **7**, 83. For an example from Woburn, see E. J. Russell and J. A. Voelcker, *Fifty Years of Field Experiments at Woburn*, p. 332, London, 1936.
[2] J. E. Gieseking, *Soil Sci.*, 1939, **47**, 1; S. B. Hendricks, *J. Phys. Chem.*, 1941, **45**, 65; see also C. R. Smith, *J. Amer. Chem., Soc.*, 1934, **56**, 1561.
[3] L. E. Ensminger and J. E. Gieseking, *Soil Sci.*, 1939, **48**, 467; 1941, **51**, 125.
[4] S. B. Hendricks, *J. Phys. Chem.*, 1940, **45**, 65.

up with dilute salt solutions of different metals, but all of constant normality, it is found that some cations are more powerful replacers of calcium from the clay surface than others. Thus, at a given ionic concentration in the solution, lithium and sodium ions are poorer displacers of base from a clay than potassium or ammonium ions, and these than rubidium or caesium; magnesium and calcium, which are about equally strong and of about the same strength as rubidium, are poorer displacers of base than strontium or barium; and the hydrogen ions from a strong acid, or polyvalent ions such as trivalent lanthanum and tetravalent thorium are still stronger displacers of bases than the divalent cations. Table 27, taken from some of K. K. Gedroiz's[1] classical papers on the subject, illustrates this phenomenon, and a further and more detailed example can be found in the work of J. E. Gieseking and H. Jenny.[2]

TABLE 27

Replacing Power of Different Cations

Milli-equivalents of Mg, Ca or Ba, displaced per 100 gm. of soil by certain cations added as chlorides

Chernozem	Mg	Ca	Ba
Conc. of chloride	0·1 *N*	0·01 *N*	0·1 *N*
Chloride added:			
Li	—	1·4	7·6
Na	13·9	1·8	9·1
K	20·4	5·0	13·5
Rb	—	5·7	15·5
NH_4	20·4	5·7	12·9
Mg	—	5·3	15·4
Ca	35·2	—	20·4

This result can be stated in the converse way; that if samples of clay each holding a different base are put in a standard salt solution, exchangeable sodium ions come out of the clay easier than exchangeable potassium or ammonium, and exchangeable magnesium comes out a little easier than exchangeable calcium, which in turn comes out easier than strontium or barium. On the whole, exchangeable potassium comes out easier than exchangeable magnesium,[3] and exchangeable barium easier than exchangeable lanthanum or thorium.

[1] *J. Expt. Agron.* (Russia), 1918, **19**, 269; 1919, **20**, 31. Manuscript translations by S. A. Waksman and published by U.S. Dept. Agric., and summarised by H. J. Page in *Trans. Int. Soc. Soil Sci.*, Comm. 2, 1926, A, 208.

[2] *Soil Sci.*, 1936, **42**, 273. See also P. Schachtschabel, *Koll. Beih.*, 1940, **51**, 199.

[3] See also R. H. Bray, *J. Amer. Chem. Soc.*, 1942, **64**, 954.

The relative tightness of binding for more complex ions has not been worked out in detail, but in general large or complex cations tend to be bound more tightly than small or simple ones. Thus diamines are more tightly held than the corresponding simple amines, and the tetra-substituted ammonium ion is still more strongly held; and large cations like methylene blue, the alkaloids such as brucine, and the proteins can all be so strongly held that it is very difficult to displace them, except with other equally large cations.[1]

The behaviour of the simple cations is not quite so regular as suggested above, for the difference between the monovalent, or alkali, cations and the divalent, or alkaline earth cations, depends on their concentration in solution. The more dilute the solution containing the cations the more powerful are the alkaline earths relative to the alkali cations as displacers of exchangeable cations; and as the ionic concentration in the solution increases, so do the replacing powers of the alkali metals relative to the alkaline earths.

S. Mattson[2] also claims that the inverse of this is true on the clay surface: clay particles having a high base exchange capacity, hence a high concentration of exchangeable ions on their surface, hold calcium relative to sodium or potassium more tightly than clay particles having a low base exchange capacity, and hence a low concentration of exchangeable ions on their surface. Thus, if a montmorillonite and a kaolin were each put in a solution of potassium and calcium chlorides, the kaolin would take up relatively more potassium in comparison with calcium than would the montmorillonite. Alternatively, plants growing in a montmorillonite soil having a given ratio of exchangeable potassium to calcium will have a higher ratio of potassium to calcium than similar plants growing in a kaolinitic soil having the same ratio of exchangeable potassium to calcium.[3] Further, as a clay becomes more acid so the effective surface concentration of simple exchangeable cations falls and the clay becomes more kaolinite-like in this respect. Thus, as the acidity of a soil rises, so it tends to hold potassium ions relatively more strongly than calcium, or to put it another way, during leaching, which causes increasing soil acidity, calcium tends to go more quickly than potassium.

This power of different clay minerals to hold pairs of ions with different intensities has been suggested as a method for recognising the clay mineral present in a soil. It is unnecessary for kaolinite, because a clay analysis or a rough base exchange capacity determination will

[1] J. E. Gieseking, *Soil Sci.*, 1939, **47**, 1.

[2] *LantbrHögsk. Ann.*, 1945, **12**, 119; with K. G. Larsson, ibid., 1945, **12**, 222; *Soil Sci.*, 1946, **61**, 313. For further examples, see A. Mehlich, *Soil Sci.*, 1946, **62**, 393; with W. E. Colwell, *Proc. Soil Sci. Soc. Amer.*, 1944, **8**, 179; C. E. Marshall, *Soil Sci.*, 1948, **65**, 57.

[3] S. Mattson, *LantbrHögsk. Ann.*, 1948, **15**, 308.

immediately show if this is the predominant mineral. The micaceous or illite type of clay can be roughly distinguished from the montmorillonite type either by its relatively greater power of holding exchangeable barium than magnesium[1] or its relatively smaller power of absorbing cerium from an acid solution.[2]

Potassium ions may show a complication in base exchange phenomena either not shown by other simple cations, or shown to a much less extent. Exchangeable potassium appears to exist in two forms, readily exchangeable and difficultly exchangeable. If a soil rather low in exchangeable potassium is left in contact with a potassium salt for a long time, and particularly if it is repeatedly wetted and dried, it will have absorbed some potassium that cannot readily be displaced by another cation. If the soil is now left in contact with some cation other than potassium for periods of several months much of this potassium will be released. And both actions appear to be base exchange reactions.

This behaviour of potassium cannot yet be explained in detail.[3] It is probably due to the potassium ion being able to fit almost exactly into the hexagonal holes in the surface oxygen sheets of the clay particles. It would then touch six oxygen atoms and almost touch a hydroxyl, so might be expected to have only a small probability of dissociating into the solution. Further, potassium ions might be able to hold adjacent clay particles together by the same mechanism as in the potash micas, by each ion fitting into two such holes, one in each sheet. The observation that this potassium fixation is enhanced by repeatedly wetting and drying the clay in the presence of potassium salts would be readily explicable on this picture. So would the observation of S. Caillère *et al.*[4] that montmorillonite which has been made to fix an appreciable amount of potassium is converted into an illite clay. Further, R. Chaminade and others[5] have shown that ammonium ions, which have a radius very similar to potassium, show this effect to a limited extent.

The Quantitative Laws of Base Exchange

Many attempts have been made to develop theoretical laws governing the distribution of cations between the solution and the absorbing complex in the soil. The task is simplified by the facts that the

[1] P. Schachtschabel, *Bodenk. PflErnähr.*, 1941, **23**, 1; 1943, **29**, 213.
[2] S. B. Hendricks and L. T. Alexander, *Proc. Soil Sci. Soc. Amer.*, 1940, **5**, 95.
[3] For recent reviews, see J. C. Martin, R. Overstreet and D. R. Hoagland, *Proc. Soil Sci. Soc. Amer.*, 1946, **10**, 94; A. K. Levine and J. S. Joffe, *Soil Sci.*, 1947, **63**, 329, 407.
[4] *C.R.*, 1948, **226**, 680.
[5] *C.R.*, 1940, **210**, 264. See also J. B. Page and L. D. Baver, *Proc. Soil Sci. Soc. Amer.*, 1940, **4**, 150; A. K. Levine and J. S. Joffe, *Soil Sci.*, 1947, **63**, 151.

equilibrium is nearly independent of temperature and the main part of the exchange takes place very rapidly. It usually takes several days for equilibrium to be reached, but this may only be an apparent equilibrium due to side reactions taking place between the salts in the solution and decomposition or other amorphous products present in the soil or clay; and if this is so, the true exchange equilibrium is probably reached very rapidly indeed.

Many workers have tried to apply the Law of Mass Action to the exchange. But one component of the system—the clay particles—cannot be treated like simple ions of definite valency, so arbitrary assumptions must be made about the behaviour of the bases on the clay surface to formulate a law at all; and different but equally plausible assumptions lead to different equations.[1] The problem really falls into two parts: the effect of the relative concentration of the cations in solution, which can be accurately determined since they are in solution; and the effect of their relative concentration on the surface of the soil particles, which is more difficult to determine accurately.

R. K. Schofield has shown that the first part of the problem is readily susceptible to accurate investigation. The principle of his method is to obtain a bed of clay or soil containing at least two different exchangeable cations and percolate through it a solution containing the same cations as the soil. The relative concentrations of the cations are so adjusted that the composition of the solution is unaffected by percolating through the bed—the cations in the solution and on the soil are therefore in equilibrium. The solution is now either diluted or concentrated, and the necessary new relative proportions of the cations in the solution are determined so that it percolates through unchanged. Using this technique, he has been able to verify to within much closer limits than previous workers the accuracy of the so-called ratio law, which he states in the following words:

> "When cations in a dilute solution are in equilibrium with a larger number of exchangeable ions, a change in the concentration of the solution will not disturb the equilibrium if the concentrations of all monovalent ions are changed in one ratio, those of all the divalent ions in the square of that ratio, and those of all the trivalent in the cube of that ratio."

Thus, using a soil containing mainly exchangeable potassium,

[1] The three main equations that have been proposed are due to H. W. Kerr, *Soil Sci.*, 1928, **26**, 384; A. P. Vanselow, ibid., 1932, **33**, 95; E. N. Gapon, *J. Gen. Chem.* (U.S.S.R.), 1933, **3**, 144. For an application of statistical mechanics methods to this problem, see H. Jenny, *J. Phys. Chem.*, 1936, **40**, 501. For a recent discussion of the validity of these equations, see W. P. Kelley, *Cation Exchange in Soils*, New York, 1948.

magnesium and calcium ions, a solution of potassium, magnesium and calcium chlorides of total concentration $N/100$ was found that would pass through the soil unchanged. He then verified that another solution containing half the concentration of potassium would only pass through unchanged if the calcium and magnesium concentrations were reduced fourfold, and confirmed that the *p*H of this solution was 0·3 units higher than that of the first solution, because the hydrogen-ion concentration in the second solution is also halved. Further, using a very acid surface soil, the solution had to contain both aluminium and hydrogen ions if it was to pass through the soil unaltered, and if in a new solution the concentration of the potassium was halved, that of the hydrogen had to be halved and of the aluminium reduced eightfold if it was to pass through unaltered. These results express in a quantitative form, and for a particular set of experimental conditions, the relation between the *p*H of a soil and the concentration of salts in the soil solution which was discussed in qualitative terms on p. 99.

This ratio law, however, probably only holds if the solution in the double layer close to the particle surface only contains cations, and since most soils contain positively charged material intimately mixed with the clay, as will be shown on p. 114, this is only true if the soil is in a solution of fairly high *p*H or if the double layer is very thick, that is, if the salt concentration in the soil solution is low. This ratio law does not hold for a soil having a positive charge comparable with or larger than its negative, as, for example, the Natal soil shown in Fig. 12. A probable alternative way of stating the conditions for the validity of the ratio law is that the anions in the percolating solution must be without effect on the *p*H and on the cation concentration in the percolating solutions, that is, it must be irrelevant if the salts used to make up the solutions are, for example, chlorides, nitrates, or sulphates, provided only that they are all soluble in the concentration required.

The problem of finding a comparable law for the effect of other changes of cation concentration in the solution on the ratio of the exchangeable cations is complicated experimentally by the uncertainty of deciding when equilibrium is reached and by ionic exchange reactions appearing to be only partially reversible. As an example of a fully reversible reaction, consider a soil and solution containing only two types of cations. The exchange reaction is then said to be reversible if the relative concentration of these two cations on the clay, when equilibrium is reached, depends only on their relative concentration in the solution, no matter what their relative abundance on the clay was at the start of the experiment. This assumption of reversibility—or of independence of past history—may be reasonably valid if both the ions have the same valency, that is, if they are both monovalent

or both divalent,[1] though Vanselow claims that the sodium-potassium exchange does not show this reversibility. But the assumption certainly does not hold if the cations have different valencies.

The base or ionic exchange equation relating the concentrations of the cations in the solution with their relative abundance on the exchange complex is probably known in the special case of all the cations involved having the same valency provided care is taken to prevent any side reactions being important. Under these conditions the experimental results are approximately in accord with the statement that the ratios of the amounts of cations on the exchange complex are directly proportional to their relative concentrations in the solution. Hence, merely adding water to the soil-salt solution system has little or no effect on the exchange, in accord with the ratio law.

No comparable generally valid statement can yet be made for the general case of the cations having different valencies. As already mentioned, the apparent equilibrium between the cations on the soil and in the solution is not reversible, and it is shifted by merely adding water to the soil-salt solution system. As an illustration of the latter effect, consider a soil containing only potassium and calcium ions apparently in equilibrium with a solution containing only these cations. Adding water to this system causes some calcium in the solution to displace some potassium from the soil, with the consequence that the proportion of calcium on the exchange complex increases and the potassium decreases.[2] Thus the statement that monovalent ions in solution become more powerful extractors of exchangeable ions relative to the divalent as their absolute concentration in the solution increases is merely a direct consequence of the ratio law.

A further result, which needs more investigation before its general validity can be accepted, concerns the effect of altering the ratio of the total volume of solution to the weight of soil on the equilibrium when the cations present have different valencies. Keeping to the example of potassium and calcium as the only two cations present, then for a given potassium-calcium ratio in the solution, the proportion of calcium in the exchange complex probably increases as the ratio of the weight of soil to the volume of solution increases.

The Anion-holding Power of Soils

Many soils differ from pure clay minerals in that in acid solutions they take up anions as well as cations. Table 28 shows the apparent

[1] For examples of work testing reversibility and the validity of various equations that have been suggested, see A. P. Vanselow, *Soil Sci.*, 1932, **33**, 95; C. E. Marshall and R. S. Gupta, *J. Soc. Chem. Indust.*, 1933, 433 T; O. C. Magistad, M. Fireman and B. Mabry, *Soil Sci.*, 1944, **57**, 371; L. E. Davis, *Soil Sci.*, 1945, **59**, 379; L. Wiklander, *LantbrHögsk. Ann.*, 1947, **14**, 1.

[2] See, for example, R. F. Reitemeier, *Soil Sci.*, 1946, **61**, 195.

TABLE 28

Uptake of Ammonium and Chloride by a Rothamsted Subsoil from an N/5 Ammonium Chloride Solution at different pHs

Uptake in milli-equivalents per 100 grams of oven-dry soil

pH	Chloride adsorbed	Positive charge	Excess of NH_4 over Cl adsorbed	Negative charge
2·05	1·5	2·0	19·5	21·5
2·3	1·3	1·8	21·3	23·1
2·6	1·2	1·7	21·7	23·4
3·1	1·2	1·7	21·6	23·3
3·3	1·1	1·6	21·7	23·3
3·8	0·6	1·1	22·3	23·4
5·5	0·0	0·5	24·0	24·5
6·2	—0·4	0·1	25·7	25·8
7·15	—0·6	—0·1	27·0	26·9
7·4	—0·5	0·0	28·2	28·2

Samples treated with Acid Ammonium Oxalate

Uptake in milli-equivalents per 100 grams of untreated oven-dry soil

2·5	—0·3	0·2	23·2	23·4
3·65	—0·5	0·0	23·5	23·5
4·15	—0·6	—0·1	23·3	23·2
7·5	—0·4	0·1	26·8	26·9

uptake of ammonium and chloride ions from a $N/5$ ammonium chloride solution at different *p*Hs by a Rothamsted subsoil from which all replaceable aluminium ions have been displaced by ammonium.[1] These positively charged spots are not an integral part of the clay crystals, but are situated on hydrated iron compounds, which contain aluminium and other ions as well, for they are entirely removed if the soil is thoroughly treated with Tamm's acid oxalate solution in sunlight; and they have no fundamental connection with the clay crystals themselves, for this treatment does not affect the base holding power of the soil, when expressed on the original weight of the soil before treatment, a result that also proves they have no power of holding bases. The composition and size of these particles are not known. They are only slightly soluble in strong acids, though they are soluble in the usual solvents for aged ferric hydroxide precipitates, and they are present in fine particles for they cannot be separated from clays merely by dispersion and centrifuging. It is possible, though not yet proved that particles of hydrated aluminium oxides, such as

[1] R. K. Schofield, *J. Soil Sci.*, 1949, **1**, 1.

AlO(OH), for example, may also carry a positive charge under suitable conditions in the soil.

These iron-rich compounds reduce the effective negative charge held by the soil whenever the conditions allow them to develop their positive charges. They do this by the hydroxyl groups on their surface accepting hydrogen ions, in an analagous way to the aluminium complexes already described on p. 96; and the positive charge developed increases with increase of the hydrogen-ion concentration of the solution which surrounds them. This can be seen in an extreme form for a Natal

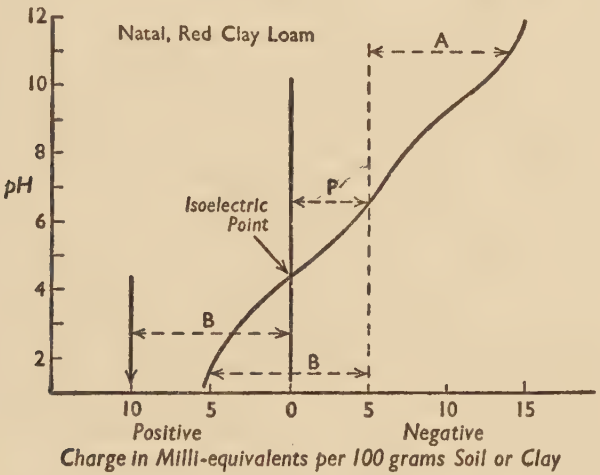


FIG. 12. The titration curve of a tropical red loam.

P is the permanent negative charge on the soil particles.
A is the additional negative charge developed at high *p*H.
B is the positive charge developed at low *p*H.
The arrow shows the maximum uptake of chloride from alcoholic HCl.

soil, whose buffer curve is given in Fig. 12. The soil particles possess a permanent negative charge of 5 milli-equivalents per 100 gm., but they can develop a positive charge of 10 milli-equivalents under suitable conditions of low *p*H. Such a soil is said to possess an isoelectric point, which occurs at *p*H 4 for this particular soil under the particular conditions of the experiment, for at this *p*H the soil is uncharged; it carries neither a net positive nor negative charge, whilst below this *p*H it is positively charged and above it is negatively, and such soils are called amphoteric. The isoelectric *p*H of amphoteric soils is not a constant, but depends on concentration and type of electrolyte present in the soil solution. Amphoteric soils are probably very rare in the temperate zones, though the power to absorb anions from strong salt solutions in acid conditions is probably very common; that

is, most soils can be made to develop some positive charges, though considerably less than their permanent negative charges.

These positive charges need not necessarily be neutralised by simple anions, for if the electrolyte concentration is not too high the double layers around the positive and the negative charges will interpenetrate with a consequent decrease in the cation concentration in the interpenetrating layers. Hence, they can only show their maximum absorption for anions when the electrolyte concentration is sufficiently high to compress the double layers so much that there is no interpenetration.[1] Unpublished work of Schofield indicates that high concentrations are needed, in conformity with the other evidence already mentioned that these iron compounds are present as very small particles intimately intermixed with the clay particles or the organic matter.

The anions held by these iron-rich compounds can take part in anionic exchange, and the tightness with which they are held depends on the type of anion.[2] The chemistry of this anionic exchange is still not known in detail. Chlorides and nitrates are only weakly held by soils having a net negative charge and can be removed completely by reducing the electrolyte concentration around the particles, so the double layer due to the negative charges on the particles interpenetrates and replaces that due to the positive charges. Other anions, such as phosphate and some polyvalent anions, are held closer to the positive charges, so that the double layer due to the negative charges cannot expel them. Hence, these anions cannot be washed out by distilled water, but need to be displaced by other anions.

The exchange and retention of phosphate anions in particular have been investigated because of their agricultural importance. They can probably be adsorbed and tightly held as monovalent $H_2PO_4^-$ ions. They can be removed by other strongly adsorbed anions such as divalent arsenate, silicate, citrate, oxalate, hydroxyl and fluoride, but possibly only the arsenate and silicate give typical exchange reactions.[3] Thus the citrate and oxalate ions may displace the phosphate more by dissolving the iron-rich material responsible for the positively charged spots than by anionic exchange, and a high concentration of hydroxyl ions normally causes some decomposition of the whole complex. The effect of fluoride is also uncertain, as more fluoride is adsorbed than phosphate displaced.

Anionic exchange in normal soils thus differs from cation exchange, in that it is not a quantitative exchange. The total quantity of anions

[1] See G. Barbier and J. Chabannes, *C.R.* 1948, **226**, 749, 1036, for experiments confirming the importance of a high electrolyte concentration for high anion adsorption.

[2] See, for example, A. Demolon and E. Bastisse, *Ann. Agron.*, 1934, **4**, 53.

[3] L. A. Dean and E. J. Rubins, *Soil Sci.*, 1947, **63**, 377; T. Kurtz, E. E. De Turk and R. H. Bray, ibid., 1946, **61**, 111.

held is not a constant, but depends on the closeness with which the anions are held and the power of the cationic double layer to displace the anionic.

Summary of the Acid and Base-holding Mechanisms in Soils

Soils contain clay minerals, organic matter and iron-rich particles, all of which can take part in these reactions. The base-holding mechanisms of organic matter will be discussed in more detail on p. 261, but a summary of the main mechanisms involved can be given here.

Soils develop negative charges, and consequently can hold bases, through the following mechanisms:

1. Permanent negative charges on the clay and other minerals due to isomorphous replacement. These minerals need not occur in the particle size range of the clay fraction, though for most soils they do. Soils containing vermiculite and other sponge-like minerals can have these minerals occuring in the silt or fine sand fraction.

2. Negative charges developed by hydrogen ions dissociating from hydroxyls attached to silicon atoms at the broken edges of the oxygen sheets, which compose the clay mineral. This reaction can be written

$$\equiv Si-OH + H_2O \rightarrow \equiv Si-O^- + H_3O^+.$$

It only occurs appreciably under neutral or alkaline conditions, and the more alkaline the conditions, the greater is the negative charge developed.

3. Carboxyl groups attached to various compounds present in the soil organic matter dissociate hydrogen ions at various *p*H ranges below 6, depending on the groups to which they are attached.

4. Hydroxyls attached to various groups in the organic matter that dissociate hydrogen ions. These are normally only important above *p*H 6, and become increasingly important as the *p*H rises into the alkaline region.

Soils contain aluminium ions which exist as trivalent ions in 6-co-ordination with water under acid conditions, but which can dissociate hydrogen ions from the co-ordinated water molecules as the *p*H rises, that is, as the conditions become less acid. These are responsible for much of the buffering of acid soils. Soils containing a high proportion of such exchangeable ions will be referred to as acid clays throughout the book, and the phrase *hydrogen clay* will not be used, as there is no evidence that hydrogen or hydroxonium ions neutralise any appreciable proportion of the net negative charge on acid soils or clays in the conditions usually met with in the field or in those that have prevailed in most laboratory experiments.

Soils also develop positive charges, and can consequently hold anions by two mechanisms:

1. Inorganic substances rich in iron that are soluble in Tamm's acid oxalate solution and which do not develop negative charges. They only develop positive charges in acid solutions, but the exact mechanism involved is not known.
2. Basic groups on the soil organic matter that also function under acid conditions. Again the groups responsible are not known, though they might be imino-nitrogen groups.

The Effect of Fertilisers on the Exchangeable Bases held by Soils

Fertilisers are salts farmers add to the soil in order to increase the supply of nutrients to the crops. But these salts contain anions and cations which may interact with the exchangeable cations held by the soil, and so alter some of the soil's properties. The principal types of fertilisers that may have such effects are:

(1) ammonium salts and organic nitrogen compounds that decompose to liberate ammonia;
(2) sodium nitrate;
(3) phosphatic fertilisers, in particular superphosphate;
(4) the potassic fertilisers.

AMMONIUM SULPHATE

The first effect of adding this to a soil is for a base exchange reaction to take place, in which the ammonium ions enter the exchange complex and an equivalent amount of other base, usually calcium, is displaced. This displaced calcium then washes out of the soil in association with the sulphate anions introduced in the fertiliser.

The ammonia is then nitrified and the nitrate ions produced are neutralised once again by calcium. In so far as the nitrate is taken up by the plant the calcium ions are free to re-enter the exchange complex, but in so far as the nitrate is leached out of the soil, an equivalent amount of calcium is leached out with it.

Hence, the effect of adding an equivalent of ammonium sulphate to the soil is for an equivalent of calcium to be lost with the sulphate, and for another equivalent of calcium to neutralise the nitrate formed, only part of which is leached out of the soil. If all the nitrate is leached out, 150 lb. of calcium carbonate would be needed to make good the loss of calcium through the addition of 100 lb. of ammonium sulphate,[1]

[1] For lysimeter determinations of this value, see M. F. Morgan *et al.*, *Soil Sci.*, 1942, **54**, 127; J. A. Bizzell, *Cornell Agric. Expt. Sta.*, *Mem.* 252, 1943.

and if none of the nitrate is lost, 75 lb. of calcium carbonate would be needed. In normal farming practice the loss of calcium carbonate comes in between these two limits: the various estimates of its loss for each 100 lb. of ammonium sulphate added being:

J. Hudig	100
B. L. Hartwell and S. C. Damon[1]	110
E. M. Crowther[2]	112
W. H. Pierre[3]	120

So long as the soil contains a reserve of calcium carbonate the loss falls on this substance and not on the exchangeable calcium. At the end of eighty years, the amounts of exchangeable bases contained in the Broadbalk plots, treated every year with 200 lb. per acre of sulphate of ammonia, are given in Table 29.

TABLE 29

Exchangeable Bases in Broadbalk Soils[4]

Milli-equivalents per 100 grams of dry soil

	No manure	Sulphate of ammonia only	Super, and sulphates of potash, magnesia and soda		
			Alone	+ Sulphate of ammonia	+ Nitrate of soda
	Plot 3	Plot 10	Plot 5	Plot 7	Plot 16
Calcium	13·57	13·60	11·96	14·61	14·39
Magnesium	0·75	0·70	0·95	0·90	1·25
Potassium	0·42	0·30	1·08	1·12	0·95

In absence of calcium carbonate, however, the replaceable calcium is removed from the soil. At Woburn the effect of adding sulphate of ammonia at the rate of 200 lb. per acre for thirty years, and 100 lb. per acre for a further twenty years is shown, on the barley plots, by the following figures.[5]

[1] *J. Amer. Soc. Agron.*, 1927, **19**, 843.
[2] *Fifty Years of Field Experiments at Woburn*, E. J. Russell and J. A. Voelcker (1936), p. 334.
[3] *J. Amer. Soc. Agron.*, 1928, **20**, 270.
[4] H. J. Page and W. Williams, *Trans. Faraday Soc.*, 1925, **20**, 573.
[5] E. M. Crowther, *J. Agric. Sci.*, 1925, **15**, 222; E. M. Crowther and J. K. Basu, ibid., 1931, **21**, 689.

Amounts of Exchangeable Calcium, Expressed as Milli-equivalents, per cent, 100 grams of Dry Soil

No manure	Sulphate of ammonia only	Nitrate of soda only	Super, and sulphate of potash		
			Alone	+ Sulphate of ammonia	+ Nitrate of soda
3·76 pH 5·4	0·89 pH 4·5	5·15 pH 5·8	5·00 pH 6·0	1·39 pH 4·8	5·36 pH 5·8

Finally, after serious loss of exchangeable calcium, the soil becomes acid, and contains soluble aluminium salts harmful to plants. The fact was established by H. J. Wheeler in Rhode Island in 1891,[1] and quite independently, but a little later, the acidity was demonstrated by J. A. Voelcker at Woburn, where, the plots being permanent, the effect is continuously demonstrated.

SODIUM NITRATE

As this soluble salt washes through the soil some of the sodium will be expected to exchange with some of the calcium. Further, as the nitrate is taken up by the plant, so again sodium ions will be left behind in the soil, which may also exchange with the calcium. There is, therefore, a possibility that repeated dressings of sodium nitrate to a soil may slowly increase the proportion of sodium ions in the exchange complex until they influence appreciably the properties of the clay.

A. D. Hall[2] long ago studied this action on the Rothamsted soil, and came to the conclusion that forty or more annual dressings of 5 cwt. per acre of nitrate of soda had spoilt the tilth on some plots on Barnfield. However, a further forty annual applications at this rate on these plots have not had any additional effect, and it is probable that the effects he observed were due to soil variability. Thus, on Broadbalk long continued application of nitrate of soda at this rate has had no measurable effect whatever on the tilth. Unfortunately no determinations of the exchangeable sodium content of these soils have been made. Further, fifty annual applications of 2¼ cwt. per acre to wheat and barley on the light soil at Woburn did not appear to affect the tilth, except possibly occasionally in wet winters. These results are in accord with a finding of M. Salomon and J. B. Smith[3] in Rhode Island that 53 annual dressings of nitrate of soda, at the rate of nearly 3 cwt. per acre, put up the exchangeable sodium from 0·16 to 0·22

[1] *Rhode Is. Agric. Expt. Sta. Third Ann. Report*, p. 31, and subsequent reports.
[2] *Trans. Chem. Soc.*, 1904, **85**, 964.
[3] *Proc. Soil Sci. Soc. Amer.*, 1948, **12**, 298.

milli-equivalents per 100 grams of soil, on a soil having a base exchange capacity of 11 milli-equivalents. An increase as small as this obviously can have no effect on the soil properties.

On the other hand, there is ample evidence that if dressings of this order are applied to a fallow soil for a period of years, the sodium nitrate will very seriously affect the tilth by breaking down the crumbs and so causing all the coarser pores to become clogged with fine material.[1] This naturally reduces both the rate water can percolate into the soil and also the air-space in the wet soil when drained. There is also evidence that annual dressings of 5 cwt. per acre applied to rubber plantations[2] and citrus orchards[3] harm the soil structure, but in both cases the harvested material sold off the plantation is low in mineral matter. There is also a strong tradition among many English market gardeners that it harms the tilth, though evidence for this belief is very hard to come by, but it may be because a heavy dressing can harm the tilth temporarily if it is concentrated in a thin layer of soil. This same result holds for the effect of adding agricultural salt (sodium chloride) to the soil in preparation for sugar-beet.

SUPERPHOSPHATE OF LIME

Of all fertilisers, this has been used in largest quantity by farmers. It is made by adding sulphuric acid to ground-rock phosphate, and contains 60 per cent of calcium sulphate, as gypsum, and 25 to 30 per cent of water-soluble monocalcium phosphate, which reacts with the soil to become an insoluble phosphate, probably the di-calcium phosphate in the first instance. This phosphate does not wash out of the soil, and only about 20 to 30 per cent appears to be taken up by the crop, the remainder reverting to forms either unavailable or very slowly available to crops.

Additions of superphosphate to a soil thus have little effect on the proportions of the exchangeable bases held by a soil, as any loss of exchangeable calcium it may cause during reversion is probably made good from the slowly soluble calcium sulphate it contains. Superphosphate has been considered, although quite incorrectly and without any field evidence, as an acid fertiliser; that is, as a fertiliser that increased the acidity of the soil. It has had no appreciable effect on the *p*H or the exchangeable calcium of the Rothamsted or Woburn soils.

[1] See, for example, H. Burgevin and S. Hénin, *Ann. Agron.*, 1939, **9**, 771; M. Fireman, O. C. Magistad and L. V. Wilcox, *J. Amer. Soc. Agron.*, 1945, **37**, 888.

[2] H. J. Hardon, *Meded. Alg. Proefsta. Landbouw.* (*Java*), 1939, No. 35.

[3] D. G. Aldrich, E. R. Parker and H. D. Chapman, *Soil Sci.*, 1945, **59**, 299. Arguments from their results are complicated because they found equivalent quantities of ammonium sulphate almost as harmful, though calcium nitrate, sodium nitrate and gypsum or ammonium sulphate and lime were without harmful effect.

POTASSIUM SULPHATE

This increases the amount of replaceable potassium, apparently at the cost of the calcium and magnesium. Some other action takes place, for a further quantity is retained by the soil in an insoluble but not exchangeable form (see p. 110).

Both at Rothamsted and at Woburn sulphate of potash is without effect on the reaction of the surface soil, though it increases the acidity of the subsoils on the acid plots,[1] possibly through the washing down by rain of the acid liberated by cationic exchange. The effect on the exchangeable bases is shown in Table 30, taken from Page and Williams's analyses of the Broadbalk soil.

TABLE 30

Exchangeable Bases in Broadbalk Soil[2]

Milli-equivalents per 100 grams of dry soil

	Unmanured	Sulphate of ammonia and super	Sulphate of ammonia, super, and sulphate of potash	Sulphate of ammonia, super and sulphate of soda
Calcium . .	13·57	15·32	14·89	16·29
Magnesium .	0·75	0·70	0·50	0·70
Potassium . .	0·42	0·32	0·89	0·32

SODIUM SULPHATE

On the Broadbalk wheat field, sodium sulphate acts rather differently from potassium sulphate. It causes no diminution in the amount of replaceable calcium or potassium, but, on the contrary, an increase in the calcium. Apparently, therefore, the sodium has not replaced calcium or potassium, yet something has certainly happened, for more potassium is taken up by the crop. The Broadbalk wheat receiving sodium, but no potassium sulphate, contains more potassium than wheat on the adjoining plot receiving no sodium sulphate (Table 31).

MAGNESIUM SULPHATE

This has the same effect. From Table 31 it appears that in the twenty-year period, 1852–71, the sodium sulphate had enabled the plant to take up an additional 219 lb. of K, whilst the magnesium sulphate has furnished it with an extra 267 lb. over and above what the crop on

[1] E. M. Crowther, *J. Agric. Sci.*, 1925, **15**, 222; E. M. Crowther and J. K. Basu, ibid., 1931, **21**, 689.

[2] *Trans. Faraday Soc.*, 1925, **20**, 573.

TABLE 31

Effect of Sodium and Magnesium Sulphates in Increasing the Supply of Potassium to the Plant[1]

	Ammon. salts only	Ammon. salts + super-phosphate	Ammon. salts + super + sodium sulphate	Ammon. salts + super + magnesium sulphate	Ammon. salts + super + potassium sulphate	Ammon. salts + super + sulphates of sodium, magnesium and potassium
1852–61	Plot 10	Plot 11	Plot 12	Plot 14	Plot 13	Plot 7
K in ash of straw, per cent . .	15·6	12·3	16·7	18·3	20·0	19·7
K in ash of grain, per cent . .	28·2	26·4	27·2	27·1	27·3	27·3
Weight of K in ten whole crops, lb.[2]	249	256	377	414	442	465
1862–71						
K in ash of straw, per cent . .	12·0	11·7	14·3	15·4	20·8	20·4
K in ash of grain, per cent . .	28·4	26·7	27·6	27·4	27·8	27·7
Weight of K in ten whole crops, lb.[2]	199	216	314	325	459	440
Total amount of K taken by crop during the twenty years, lb. . .	448	472	691	739	901	905

Weight of Na, K and Mg added annually about 52, 83 and 45 lb. per acre respectively.

Plot 11 obtained. The calcium sulphate present in the superphosphate, on the other hand, has had no appreciable effect.

CALCIUM OXIDE AND CALCIUM CARBONATE

These are among the oldest of manures. Thus Pliny[3] described with evident approbation the method which the Belgae used for chalking land, and his description held almost exactly for the traditional method followed until about the end of the nineteenth century in the English Home Counties.[4] Their effect in neutralising soil acidity and saturating the clay and humus complexes with calcium has already been discussed (p. 104). Both oxide and carbonate have in general the same action in the soil, except that the oxide used in large quantities may have a partial sterilising effect.

[1] J. B. Lawes and J. H. Gilbert, *Trans. Chem. Soc.*, 1884, **45**, 305.
[2] About one-quarter is in the grain and the rest in the straw.
[3] *Naturalis Historiae*, Lib. 17, Cap. 4.
[4] E. J. Russell, *J. Bd. Agric.*, 1916, **23**, 625.

Calcium carbonate may also bring clay soils into a better physical tilth (see p. 408). It protects both potassium and magnesium against loss by leaching, as shown in the extensive lysimeter experiments at Knoxville, Tennessee.[1] It does not, however, as the older agricultural chemists supposed, liberate potassium from its insoluble compounds.[2] But it increases the activity of the soil population if the soil has been very acid, and this will liberate plant nutrients locked up in the soil organic matter. This in turn will stimulate plant growth and in pastures may so increase the amount of plant residues added to the soil that the humus content of the soil may be unaffected, or even slightly increased.

Heavy dressings on light soils may cause chlorosis or other nutritional diseases due to deficiencies of phosphate, iron, manganese and boron (p. 479).

[1] W. H. MacIntire, W. M. Shaw and J. B. Young, *Soil Sci.*, 1923, **16**, 217; confirmed also by J. Hendrick, *Trans. Highl. Agric. Soc. Scot.*, 1930, **42**, 1; O. C. Magistad, *Soil Sci.*, 1940, **30**, 243, who shows that calcareous soils have a lower rate of leaching of potash than have non-calcareous soils.

[2] For the literature, see O. H. Sears, *Soil Sci.*, 1930, **30**, 325.

CHAPTER VIII

THE BEHAVIOUR OF SOILS AND CLAYS IN WATER

A CLAY PARTICLE, surrounded with water, affects the properties of the water in its immediate neighbourhood; and one of the most important properties affected is the free energy of the system, for when a dry clay is wetted energy is released. This reduction in the free energy can be demonstrated in many ways. When a dry clay is immersed in water, the energy released appears as heat and the heat evolved per gm. of dry soil or clay is called its heat of wetting. When a clay holds a small amount of water, it holds it so tightly that the vapour pressure of the water is very much reduced; and the curve relating the moisture content of the clay to the vapour pressure of water in the atmosphere with which it is in equilibrium may give some information on the way in which the water is held. When the density of a dry clay is determined in water and in a non-polar hydrocarbon, e.g. carbon tetrachloride, it is found that the clay has apparently a higher density in the water than in the hydrocarbon, due to the water molecules being orientated and held in the neighbourhood of the clay surface, so occupying a smaller volume than free water molecules.

It is very important to realise that soils and clays can affect the properties of water in two ways. If the clay is immersed in water its effect on the water is due solely to the properties of its surface. But if the clay or soil only contains a small quantity of water between its particles, so that there are interfaces between the liquid water and the atmosphere, these interfaces will be strongly curved and will directly affect the free energy of the liquid water. These effects are known as capillary phenomena, and are due to the geometry of the system and not to the properties of the solid particles. They are of fundamental importance when the movement of water in the soil is being considered, and will therefore be discussed in Chapter 19.

A clay particle immersed in water affects the water molecules largely through the exchangeable ions on or near its surface. If the water is either free from electrolytes, or only contains very low concentrations, a proportion of the exchangeable ions dissociate from the soil surface and move into the water, but the majority do not move very far away from the surface. They form what is known as a diffuse double layer: a double layer because the clay surface carries a net negative charge and the water a net positive charge, and diffuse because the net positive

charge is distributed throughout a volume instead of over a surface. The properties of these double layers and the effect of other salts on the distribution of the dissociated cations in the neighbourhood of the soil surface can be calculated approximately in certain simple cases by the methods first introduced by G. Gouy and extended by P. Debye and E. Hückel.

Four properties only of this double layer need be stressed in this section. Firstly, its thickness, that is, the mean distance the ions dissociate away from the surface, decreases as the electrolyte concentration in the water increases; and at equal equivalent concentrations of electrolyte divalent cations decrease the thickness of the double layer more strongly than monovalent, and trivalent more strongly than divalent. As a corollary to this, if clay particles are suspended in water containing very little electrolyte, the double layer is thicker if the exchangeable ions are sodium and potassium than if they are calcium or magnesium, and it is probably thicker for sodium than for potassium.

Secondly, the existence of this diffuse double layer causes an electrical potential difference between the surface of the clay particle and the bulk of the solution; that is, work must be done to transfer a cation from the surface of the particle to the bulk of the solution. Hence, this double layer hinders the free interchange of cations between these two regions. A consequence of this effect has already been mentioned on p. 99. Hydrogen ions cannot have the same activity throughout these regions, and in fact the thicker the double layer the smaller will be the contribution of the hydrogen ions that can dissociate from the clay surface to the hydrogen-ion concentration in the bulk of the solution. The more the diffuse double layer is compressed on to the clay surface the more freely will the hydrogen ions be able to move from the clay surface into the solution, and the lower will be its apparent *p*H. Also, since at a given concentration calcium ions compress the double layer more strongly than potassium, a soil will have a lower *p*H in a dilute calcium chloride solution than in a potassium chloride solution of the same normality. This result is not confined to hydrogen ions. If, say, a sodium clay is dispersed in pure water, adding a dilute electrolyte to the solution will increase the proportion of sodium ions that dissociate from the clay surface through reducing the potential difference across the double layer.

Thirdly, the proportion of the exchangeable cations that dissociate to form the double layer. The most direct way of estimating this proportion is by measuring the activities of the cations around the clay particles, using suitable membrane electrodes in the same way as the hydrogen-ion concentration around the clay particle is measured with, say, a glass electrode. At corresponding contents of exchangeable base

only about one-tenth as many calcium as sodium ions are dissociated from a montmorillonite clay, though the ratio is between one-quarter and one-half that of sodium from a kaolinite, and only about one to three sodium ions per thousand adsorbed is dissociated.[1]

Fourthly, the concentration of the added anions in the diffuse double layer is lower than in the bulk of the solution. Hence, if a dilute solution of sodium chloride is added to a dry clay, and if no chloride is taken up by the clay, the concentration of chloride in the solution will rise, because the chloride will be partially expelled from that part which is near the clay surfaces from which exchangeable cations dissociate. This phenomenon is sometimes called negative adsorption;

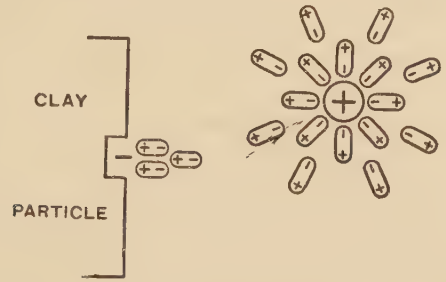


Fig. 13. Diagrammatic representation of a clay micelle dispersed in water.

and part of the water forming the diffuse double layer is sometimes called bound or unfree water; and because of this phenomenon some workers, such as S. Mattson in particular,[2] have treated the system clay-electrolyte-water as a Donnan membrane equilibrium system. This exclusion of anions from part of the water in the system also creates great difficulties when one is trying to measure the adsorption of anions by soils, particularly monovalent anions such as chlorides and nitrates which are only taken up in small quantities; for one does not know experimentally from what effective volume of water the anion is expelled.

The exchangeable ions affect the water through the positive charges they carry influencing the orientation of the water molecules in their neighbourhood, for though the water molecule is electrically neutral, it has an excess of positive charge at one end and of negative charge at the other, so behaves like an electric dipole. Fig. 13 illustrates this effect diagrammatically. The free negative charges on the clay surface, and the dipole formed by a negative charge on the clay neutralised by an undissociated cation, equally affect the orientation and freedom of movement of the water molecules in their immediate neighbourhood.

[1] C. E. Marshall, *Soil Sci.*, 1948, **65**, 57.
[2] For a recent paper of his, see S. Mattson and K. G. Larsson, *Soil Sci.*, 1946, **61**, 313.

This effect of the cation in reducing the freedom of movement of the water molecules is greater the greater the charge on the cation, and the smaller its size, that is, the greater its surface charge density. Thus magnesium ions have a greater effect than calcium, and calcium than potassium. Hence, magnesium clays have a greater heat of wetting,[1] a greater adsorption of water vapour at low relative humidities,[2] and a greater apparent density in water compared with that in an inert liquid[3] than calcium clays and these than sodium clays and these than potassium clays. These ionic effects are not confined to the system clay-water, but are also shown, usually to a smaller extent, with clay and any other liquid whose molecules possess dipole moments, such as the alcohols, for example. They are not shown by systems in which the clay is dispersed in a non-polar liquid, such as in most hydrocarbons or carbon tetrachloride.

Absorption of Liquids and Gases by Dry Clays

Dry clays absorb liquid by two distinct mechanisms. Firstly, molecules of the liquid can be held by the electric charges of the clay and the exchangeable ions, provided they possess a dipole moment or have a dipole moment induced in them by the charges. E. W. Russell[3] has made a fairly extensive investigation of these absorption phenomena and found that simple electrical considerations are quite adequate to explain them. Secondly, liquids can be held in the pores between the clay particles, and any liquid can be held in such a way. R. K. Schofield[4] showed that there is no reason to doubt that the ordinary laws of capillary condensation hold approximately even if the pores are only about ten times larger than the diameter of the liquid molecules.

The adsorption of liquids on the surface of dry clays normally involves the system swelling if the particles were previously in closest packing, though the additional volume occupied is usually considerably less than the volume of liquid adsorbed, for much of the adsorbed liquid occupies the pore space between the particles. A good quantitative analysis of the factors causing a dry clay to swell when wetted with water has not been made, but normally the swelling is greater the higher the base exchange capacity of the clay, as one would expect; and for a given clay the sodium saturated usually swells more than the calcium saturated and the acid washed, and these swell more than the potassium saturated.[5] As will be mentioned on p. 134, the swelling is

[1] W. W. Pate, *Soil Sci.*, 1925, **20**, 329; L. D. Baver, *J. Amer. Soc. Agron.*, 1928, **20**, 921; M. S. Anderson, *J. Agric. Res.*, 1929, **38**, 565; H. Janert, *J. Agric. Sci.*, 1934, **24**, 136.
[2] M. D. Thomas, *Soil Sci.*, 1928, **25**, 485; H. Kuron, *Koll. Chem. Beih.*, 1932, **36**, 178.
[3] *Phil. Trans.*, 1934, **233** A, 361.
[4] *Trans. 1st Comm. Int. Soc. Soil Sci.*, Bangor, 1938, A 38.
[5] L. D. Baver and H. Winterkorn, *Soil Sci.*, 1934, **38**, 291; 1935, **40**, 403.

less in a salt solution than in water, and all the ionic clays behave similarly. If the liquid merely fills the spore space without being specifically adsorbed on the surface, as, for example, if a non-polar hydrocarbon vapour condenses on a dry clay whose particles are in closest packing, the condensation will involve no change in the volume of the clay system.

The converse process of dispersing a clay in a liquid and then removing the liquid by allowing it to evaporate, causes the volume of the clay-liquid system to be reduced by the volume of the liquid removed until a time comes when further removal of liquid allows air to enter the spaces between the clay particles. If the liquid is not specifically adsorbed by the clay surface, further removal of liquid will only cause a small reduction in volume of the system as the particles will be nearly in closest packing, so further drying cannot bring them much closer together. But if the liquid is specifically adsorbed, as is water, for example, then the thickness of the adsorbed films round the particles will become thinner and the whole system continue to shrink.

Dry clays will also absorb gases, and here we know very much less about the phenomenon and nothing about the mechanism of the absorption. At temperatures of liquid nitrogen (−183°C.), P. H. Emmett, S. Brunauer and K. S. Lowe[1] considered they could calculate from the nitrogen absorption curve the point at which a monomolecular film of nitrogen was formed on the clay surface; and using this method, concluded that the particles in the clay fraction of two soils (Cecil and Barnes) had a surface area of about 40 and 70 sq. m. per gm.

Dry clays absorb permanent gases at room temperatures, and the amount they absorb is in proportion to the gas pressure, and increases as the critical temperature increases. The absorption is very small for helium, neon and hydrogen, larger for oxygen, nitrogen, air and argon,[2] and much larger for carbon dioxide.[3] These absorbed gases are readily displaced by water vapour or water, and, in fact, this displacement of absorbed air is an important mechanism in the observed break-up of dry soil clods when they are wetted.[4]

This is illustrated in Fig. 14, which shows the changes in volume of a wet soil cylinder as it is first dried and then re-wetted.[5] The higher volume for a given moisture content on re-wetting is due to the adsorbed air that has been displaced and entrapped in the pores.

[1] *Soil Sci.*, 1938, **45**, 57; R. A. Nelson and S. B. Hendricks, ibid., 1943, **56**, 285.

[2] Unpublished observations of E. W. Russell and G. H. Cashen.

[3] H. Wiessmann and W. Neumann, *Ztschr. Pflanz. Düng.*, 1935, **40**, 49; *Trans. 3rd Int. Cong. Soil Sci.* (Oxford), 1935, **1**, 51; M. W. Tschapek, *Pedology*, 1938, No. 1, 25.

[4] For examples of this effect, see E. W. Russell and R. V. Tamhane, *J. Agric. Sci.*, 1940, **30**, 210.

[5] W. B. Haines, *J. Agric. Sci.*, 1923, **13**, 296. For further examples of this effect, see E. W. Russell and R. V. Tamhane, ibid., 1940, **30**, 210.

The quantities of the permanent gases absorbed at normal temperatures and pressures is far less than that required to give a monomolecular layer, and the position of the absorbed molecules on the clay surface is unknown. It is possible that calcium and magnesium clays absorb gases more strongly than potassium clays, which in turn are stronger absorbers than sodium.[1]

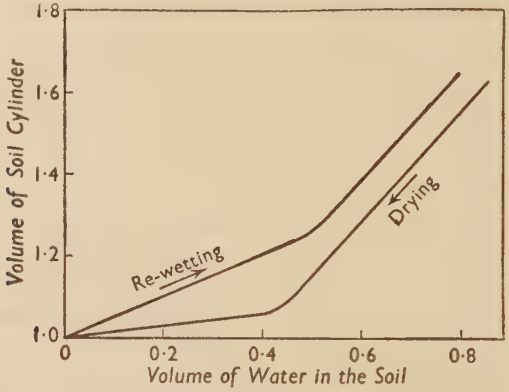


Fig. 14. The effect of drying and wetting a cylinder of moulded soil on its volume.

Deflocculation and Flocculation of Clay Suspensions

If a small amount of sodium clay is shaken up in distilled water it will usually disperse into individual particles, which will repel one another if they come sufficiently closely together; and when the clay particles sediment out, the sediment is compact and difficult to redisperse. This suspension is said to be deflocculated. The cause of the repulsion is due to the interaction of the two diffuse double layers, and of the compact sediment is that the particles are in close packing as they are uniformly distributed throughout the sediment. If now sufficient electrolyte is added, the particles will cease to repel one another when they come close together, but instead will stick to each other, forming loose aggregates or flocs. The suspension is now said to be flocculated. The mechanism of floc formation is not understood, but it only takes place when the diffuse double layer is thin, and since the flocs are very loose the particles can presumably only join up in chains, thus enclosing a large volume of solution. These flocs settle into loose sediments, in which the particles are not uniformly distributed, and hence which can be very easily redispersed.

The phenomenon of deflocculation in clay suspensions is shown most strongly by clays whose exchangeable ions are predominantly sodium,

[1] M. W. Tschapek, *Pedology*, 1938, No. 1, 25.

or probably also lithium. It is less strongly displayed by potassium or magnesium, and still less by calcium or acid clays. The minimum concentration of cations needed to cause flocculation is highest for sodium and lithium clays, lower for potassium, ammonium and magnesium clays, lower still for calcium and aluminium clays, and very much lower for clays containing multivalent or complex cations.[1]

The transitions between deflocculation and flocculation presents phenomena which are not well understood, though they are probably of very great practical importance. If the clay suspension is very dilute, with only a few parts of clay per ten thousand parts of water, the transitional phenomenon is that at electrolyte concentrations inadequate to cause complete flocculation, a portion of the particles stick together in very small and apparently fairly compact flocs and settle through a cloudy suspension. When the clay concentration rises to several parts per thousand of water, this phenomenon of fine flocs settling through a cloudy suspension is still the first to be seen. But as more electrolyte is added a new phenomenon is found. The clay suspension sets into a very weak gel, from which water separates out, allowing the whole to settle uniformly. The clay suspension has a sharp upper boundary and leaves a clear, supernatant liquid. On standing, this gel may break up into flocs, or it may develop pipes through which the liquid, which has become surplus through the contraction, can escape.[2] As the electrolyte concentration becomes still higher, this stage either lasts a very short time before it breaks up into flocs, or flocs form straight away.[3]

This property of forming weak elastic gels, that break up readily in a fluid suspension when shaken, is known as thixotropy.[4] It is displayed most strongly by clays such as bentonites when they hold a large amount of exchangeable sodium ions, and much more weakly by kaolinitic clays, which can only hold small amounts of exchangeable sodium. The cause of this behaviour is not known, but since it takes a definite time for the clay to set as a gel after shaking, the clay particles presumably must take up preferred orientations with respect to their neighbours.[5]

Two distinct theories, both of which may be true in part simultaneously, have been put forward to explain what is happening to these

[1] For a discussion and references to experiments on these topics, see G. Wiegner, *J. Soc. Chem. Indust.*, 1931, **50**, 65 T, and E. W. Russell, *J. Agric. Sci.*, 1932, **22**, 165. See also H. Jenny and R. F. Reitemeier, *J. Phys. Chem.*, 1935, **39**, 593, for later experiments.

[2] See R. K. Schofield and B. A. Keen, *Nature*, 1929, **123**, 492, for a photograph of this.

[3] For a more detailed description of these phenomena, see J. L. Russell, *Proc. Roy. Soc.*, 1936, **154** A, 550.

[4] This phenomenon is discussed in text-books of colloid chemistry, but for a good account, see H. Freundlich, *Thixotropy*, Paris, 1935.

[5] For a review, see E. A. Hauser, *Chem. Rev.*, 1945, **37**, 287. See also *J. Phys. Chem.*, 1939, **43**, 1015.

clay particles. On one theory, the clay particles are pictured more or less uniformly distributed throughout the system and repelling their neighbours with forces acting over distances of the order of 100 mμ (1,000 Å. or 10^{-4} mm.); but for a long time it was doubted if charged particles surrounded by a diffuse double layer could exert appreciable repulsion on similar particles at such separations. The work of H. C. Hamaker,[1] I. Langmuir,[2] S. Levine[3] and R. K. Schofield[4] has shown, however, that such long-range forces between charged particles are to be expected under some circumstances. On the other theory the clay particles are pictured as sticking together into chains forming a very open structure, and hence enclosing large volumes of liquid. This theory gives the most probable picture of the cause of gel formation in gelatin and other similar jellies, and also of the conditions prevailing in clay suspensions at floc formation, but the details of the transition from the hypothetical uniform distribution of clay particles throughout the system at the beginning of thixotropic gel formation to the open chains formed at its break-up have not been elucidated.

Deflocculation and Flocculation in Clay Pastes and Clods: Soil Consistency

Flocculation and deflocculation phenomena in concentrated clay pastes are primarily concerned with their rheological properties, i.e. those concerned with the mechanics of their flow and deformation. At a given clay concentration, a deflocculated clay is more fluid than a flocculated, and correspondingly a flocculated is more rigid than a deflocculated, but this rigidity itself is only strongly shown if the paste is subject to weak stresses; that is, it possesses a property analogous to its thixotropic properties in dilute suspensions.

Deflocculated pastes dry to hard, uniform and usually large clods possessing very few cracks, whilst flocculated pastes dry to smaller, more crumbly clods, usually full of cracks. This effect can be seen in Plate V, which shows the effect of drying a deflocculated and a flocculated paste of a sodium clay. Thus, both the uniformity of distribution of particles throughout the system that is characteristic of the deflocculated system, and the non-uniform spatial distribution characteristic of the flocculated system, persist in the dried state. Crumb formation is thus seen to be a characteristic of a flocculated, and hard clod formation of a deflocculated, clay; and the greater the

[1] *Rec. Trav. Chim. Pays-Bas.*, 1936, **55**, 1015; 1937, **56**, 1, 727.
[2] *J. Chem. Phys.*, 1938, **6**, 873.
[3] *Proc. Roy. Soc.*, 1939, **170** A, 145, 165; *J. Chem. Phys.*, 1939, **7**, 831; *Trans. Faraday Soc.*, 1939, **35**, 1125, 1140.
[4] *Trans. Faraday Soc.*, 1946, **42** B, 219.

concentration of salts present in the wet clay paste, the weaker, more friable and more porous will be the clods formed when the paste is dried.

Clods formed by drying a deflocculated clay paste differ in another fundamental respect from those formed from a flocculated paste: on wetting, the former typically redisperse into a paste; whereas the latter may swell in the water, but they retain their shape, and do not redisperse. Clods showing the former behaviour are called water-unstable, and the latter water-stable. Soils containing much exchangeable sodium but no free salts give typical hard large clods when dry, which break down again into a liquid mud when wet, whereas salt-free calcium soils give smaller clods which retain their shape on wetting. Potassium and magnesium soils come intermediate: soils rich in high base exchange capacity clays saturated with either of these bases give clods showing considerable water-instability; whereas acid soils behave almost exactly like calcium ones.

Water instability of clods is confined to those produced from drying a deflocculated paste. Thus, if sufficient sodium chloride or sulphate is added to a sodium clay paste so that it becomes flocculated, the clods formed by drying this paste become water-stable; and sodium clay clods themselves are stable if wetted with a dilute sodium chloride solution. These properties are of great importance in many irrigated soils which contain much exchangeable sodium (see Chap. 33). So long as fairly salty irrigation water is used the surface tilth remains good, but the soils cannot stand prolonged rain, because rain-water does not contain enough salts to keep the clay particles flocculated. These harmful effects of deflocculated sodium soils can often be aggravated by adding small quantities of sodium carbonate (alkali), which by raising the *p*H raises the exchangeable sodium content of the soil, causing it to become deflocculated.

The cause of the water stability or instability of clay crumbs is not known, nor is there of necessity a sharp distinction between these two conditions, for one can have crumbs showing all transitions between great stability and great instability in water. Water-unstable crumbs form a more or less reversible system with water: the relative positions of the clay particles depend primarily on the amount of water present rather than on their previous relative positions, and if extra water is added, it can penetrate relatively freely between the clay particles. Water-stable crumbs, on the other hand, form a more irreversible system with water: once the clay particles have taken up certain positions relative to their neighbours, additional water can no longer penetrate freely between them. The mechanism of the inter-particle bonds that hold them together in these stable configurations is unknown.

It is only present when the clay is flocculated and, hence, presumably when the diffuse electric double layer is poorly developed; and its existence implies that the large volume occupied by flocs in dilute or moderately dilute suspensions must be due to this bond holding clay particles together in chains enclosing large volumes of solution.

Flocculation and deflocculation of clay pastes affect other properties besides water stability. Deflocculated clay pastes are sticky, and mouldable into any desired shape at relatively low moisture contents; flocculated pastes are less sticky, and cease to be mouldable at relatively high moisture contents—they become crumbly or friable at lower moisture contents. This complex factor of lack of stickiness together with crumbliness probably is that recognised in the field as mellowness: a mellow tilth takes cultivation implements at higher moisture contents than a raw tilth, and dries to a crumbly friable soil rather than to hard clods.

Adding calcium carbonate to a heavy clay soil may increase the mellowness of its tilth and reduces the size of clods into which the soil dries, presumably through it causing the clay to become more flocculated. It is, however, not due to it converting an acid clay into a calcium clay, for both these clays behave almost identically in the absence of added electrolyte.

Flocculation and deflocculation also affect the swelling of soils when wetted. A deflocculated soil swells much more than a flocculated one, presumably due to water films being able to surround and separate every clay particle. This phenomenon has often been explained as due to the sodium ion being more hydrated than the calcium, for a sodium soil swells more, and holds more water than the corresponding calcium soil if it is in equilibrium with a very damp atmosphere, say, one over 90 per cent relative humidity. But it is much more likely to be due to the increase in pore space consequent upon the swelling of the deflocculated clay, for at relative humidities below 75 per cent the calcium clay holds more water than the sodium, and under very dry conditions considerably more.[1]

[1] E. W. Russell, *Phil. Trans.*, 1934, **233** A, 361 (loss by ignition of dry clays); S. B. Hendricks *et al.*, *J. Amer. Chem. Soc.*, 1940, **62**, 1457 (thermal analysis); A. M. Buswell and B. F. Dudenbostel, ibid., 1941, **63**, 2554 (infra-red analysis).

CHAPTER IX

THE PHYSIOLOGY OF THE MICROBIAL POPULATION

The Microbial Population of the Soil

Soils differ from a heap of inert rock particles in many ways, but one of the more important is that they have a population of micro-organisms living in them which derives its energy by oxidising organic residues left behind by the plants growing on the soil or by the animals feeding on these plants. In the final analysis the plants growing on the soil subsist on the products of microbial activity, for the micro-organisms are continually oxidising the dead plant remains and leaving behind, in a form available to the plant, the nitrogenous and mineral compounds needed by the plants for their growth. On this concept a fertile soil is one which contains either an adequate supply of plant food in an available form or a microbial population which is releasing nutrients fast enough to maintain rapid plant growth; whilst an infertile soil is one in which this does not happen, as, for example, if the micro-organisms are removing and locking up available plant nutrients from the soil.

The soil micro-organisms can be classified into major divisions, such as the bacteria, actinomycetes, fungi and algae—the microflora, and the protozoa, worms and arthropods—the microfauna and fauna. But these divisions are not always clear-cut: there are flagellates, such as *Euglena*, that can be classed either with the algae or protozoa, but even more important, there are groups of soil organisms such as the *Myxomycetes* and the *Acrasiae*, which seem to bridge the gap between the microflora and the microfauna and cannot be clearly assigned to either of these groups. For this reason some biologists have introduced the word "protista" to cover all micro-organisms. Protista are not considered plants or animals, but they contain many simple forms of life, some of which have given rise to plants, some to animals, and some to forms that are not clearly either, as, for example, the fungi.

The classification of the soil micro-organisms into orders and genera also presents very difficult problems. The traditional fundamental criteria on which such classification depends are based on an examination of the sexual reproductive organs; but many groups of soil organisms have either never possessed the power of sexual reproduction, as in the bacteria, actinomycetes and blue-green algae, or have

effectively lost it, as in many of the soil fungi; so that, for these groups, the generally accepted criteria are not available.

The bacteria form an outstanding example of the difficulties of classification, because not enough is yet known about them for there to be adequate criteria available to separate them into groups.[1] Their shapes are too similar for most of them to be classified by this means, and it seems unlikely that they will be found to possess sufficiently numerous surface characteristics, even when examined with the electron microscope (see Plate VI) for any detailed morphological classification to be possible. Their early classification was developed by pathologists, who were impressed by their specificity, in, for example, their being the cause of an identifiable disease; but the outstanding characteristic of the common soil bacteria is their adaptability rather than their specificity.

The methods of studying what the micro-organisms do in the soil are again very inadequately developed. There are still no satisfactory ways of following what the smaller micro-organisms do, though there are a variety of methods giving partial pictures of their activities. The method of examining a natural soil directly with a microscope, using incident light illumination, has been developed by W. L. Kubiena,[2] and though of considerable value for the study of the larger organisms, e.g. fungi and nematodes, it is still limited by great technical difficulties in the study of bacteria and other organisms that have almost transparent bodies.

J. Rossi and S. Riccardo[3] and N. Cholodny[4] independently devised a method for the direct examination of the soil organisms. Microscope slides or cover slips are buried in the soil for a few days, and carefully dug up, the main lumps of soil removed and the micro-organisms on the slide fixed and stained. Such preparations often give an excellent idea of the methods of growth and of the morphology of the different types of micro-organisms, and one can sometimes even see that one organism has been feeding on another. But the results obtained by this method must be carefully interpreted. In the first place some organisms will grow better on a continuous solid surface than in between the soil particles, hence will develop more strongly on these slides than in the soil. In the second, it has been customary to examine these slides after the organisms have been killed, fixed and stained, so that only their gross morphology, that is, whether they are cocci, rods, fine hyphae, etc., could be noted, and only rarely were fruiting bodies found.

[1] For a recent discussion of this problem, see C. B. van Niel, *Cold Spring Harbor Symp.*, 1946, **11**, 285.

[2] *Micropedology*, Ames, 1938.

[3] *Nuovi Ann. dell' Agricolt.*, 1927, **7**, 92, 457. For a summary of Rossi's work in English, see *Soil Sci.*, 1936, **41**, 53.

[4] *Arch. Mikrobiol.*, 1930, **1**, 620.

Techniques such as phase contrast microscopy have, however, now been developed which allow direct examination of the living organisms to be made.

Cholodny[1] has introduced two other methods for observing the behaviour of micro-organisms in the soil. In the first, some moist natural soil is carefully sifted into a glass cell, about 1 mm. deep, with a circular space about 4 mm. in diameter left in the middle, and the cell is then covered with a cover slip. After an interval of time, fungal hyphae may be seen growing out from the soil into this space, and later it is sometimes also possible to see films of bacteria spreading around its periphery. In the second method[2] some fine soil particles are put on a microscope slide, covered with a cover glass, and a drop of water allowed to spread between the two. This is incubated for several days and then examined. Fungi and actinomycetes are seen to be dominant if the soil is only slightly damp, whilst if it is moister films of bacteria, either cocci or short rods, can be seen to spread out radially from the soil particles. These bacteria usually appear to be surrounded by gummy capsules.

Recently C. Rouschel and S. Strugger[3] and P. C. O. Jones and J. E. Mollison[4] have developed techniques which allow one to see the bacteria and other micro-organisms in the soil. Rouschel and Strugger found that the dye, acridine orange, when absorbed by living (or recently dead) organisms fluoresces green, but when absorbed by dead cells or organic matter fluoresces red to red-brown. Jones and Mollison found that living (or recently dead) organisms would absorb aniline blue and hold it against a solvent that would remove it from organic matter and dead cells. Bacteria, actinomycetes and living fungal mycelium all stain an intense blue colour by this technique, and can be clearly distinguished from any soil or organic particles they may be on, and some of their photographs are reproduced in Plate VII.

Another group of methods for studying the soil organisms is based on the pure culture plating technique. The soil is shaken up with water and a sample of the soil suspension is diluted, mixed with a suitable culture medium and poured on a plate of nutrient agar. Organisms from the individual colonies can then be picked out and their metabolism and behaviour studied in isolation. This method picks out from among the common soil organisms those that can be brought into suspension by this technique and which will grow on the particular nutrient medium used; it can also be used to pick out less common organisms that possess any easily recognisable characteristic; but it suffers from

[1] *Arch. Mikrobiol.*, 1934, **5**, 148. [2] *Arch. Mikrobiol.*, 1936, **7**, 286.
[3] *Naturwiss.*, 1943, **31**, 300; *Canad. J. Res.* 1948, **26** C, 188.
[4] *J. Gen. Microbiol.*, 1948, **2**, 54.

the defect that usually only a small proportion of the soil micro-organisms appear to develop on these plates (see p. 147), and hence one cannot conclude that the organisms so isolated are a representative sample of the microbial population. Further, it only gives limited information about the reactions the various bacteria actually carry out in the soil, for bacteria can grow on organic substances in pure culture that they would be unable to use in the very competitive environment of the soil.

A third method, developed by Beijerinck and Winogradsky, and of great value in isolating organisms having an "unusual" metabolism, is to alter the soil conditions so they are especially favourable to organisms capable of this metabolism, but unfavourable to other types. Thus Winogradsky was able to encourage bacteria which could derive their energy from the oxidation of ammonia or nitrite by supplying the soil with ammonia or nitrite as the sole source of energy.

These various methods thus supplement each other. The methods of direct observation show something of what the micro-organisms look like in the soil, and often where they live, but only rarely do they show what they are doing; whilst the pure culture methods usually give some indication of what the micro-organisms can do, but not what they look like, or where they are, in the soil.

The Nutrition of the Microflora: Autotrophic and Heterotrophic Organisms

Organisms need food for two distinct purposes: to supply energy for their necessary vital processes and to build up their body tissues. Some of the microflora can use entirely different sources of food for these two purposes, whereas for others and for most animals the same food serves both purposes equally. The microflora use three different methods for obtaining energy: most algae and a few kinds of bacteria can use sunlight direct, some bacteria can use part of the energy set free when certain inorganic compounds are oxidised, e.g. hydrogen or sulphides, whilst most of the microflora can use part of the energy set free when sugars and other organic compounds are degraded or oxidised.

The microflora are classified into autotrophs, which are capable of using the carbon of carbon dioxide as the sole source of carbon for their body tissues, and heterotrophs, which are not so capable. Most autotrophs can utilise more complex forms of carbon, and many heterotrophs need carbon dioxide as well as complex sources of carbon. On this definition, there is a sharp distinction between heterotrophs and autotrophs, for the autotrophs must be supplied with an external

source of energy for the conversion of carbon dioxide into body protoplasm, whilst the heterotrophs can use sugars and other simple organic substances as a source both of energy and of protoplasm. There is also another important distinction between these two types of nutrition, for it takes far more energy to convert carbon dioxide than sugars into protoplasmic substances. Green plants, most algae and some bacteria are capable of autotrophic growth, whilst most bacteria, and possibly all actinomycetes and fungi, can only grow heterotrophically.

Autotrophic organisms are the primary producers of organic matter; and though the higher green plants are usually the most important suppliers of energy-rich material to the soil, some of the autotrophic micro-organisms may contribute appreciably. Autotrophic organisms fall into two groups: the photosynthetic group, which contain chlorophyll of one kind or another and are capable of using the energy of sunlight to reduce carbon dioxide to sugars, and the chemosynthetic group, which have to carry out ancillary inorganic oxidations to obtain this energy.

The typical photosynthetic organisms are the algae and green plants, though there are some photosynthetic bacteria in the soil. These latter differ from algae and green plants in that they do not produce free oxygen as the result of photosynthesis, but can only oxidise a substrate, such as hydrogen to water, hydrogen sulphide either to sulphur or to sulphate, or they can oxidise simple organic compounds. The process of photosynthesis is now looked upon as two coupled processes,[1] in one of which hydrogen ions are transferred from water molecules either to carbon dioxide or, more probably, to some compound already containing the fixed carbon dioxide, and another in which the hydroxyl ions are converted into water by the removal of oxygen. Plants can get rid of this oxygen as free oxygen, but the photosynthetic bacteria cannot; they can only give it up to a hydrogen donor or an oxygen acceptor. It is the donor or acceptor function of the hydrogen gas, the hydrogen sulphide or the oxidisable or hydrogen-donating organic substance that is essential in the bacterial photosynthetic process. Such bacterial transfer of oxygen from the hydroxyls to some other compound does not require as much energy as when it is liberated as free oxygen, hence photosynthetic bacteria cannot store up as much energy per mol of carbon dioxide fixed as can green plants, with the consequence that they are relatively poorer suppliers of energy-containing material to the soil than are the green plants.

Chemosynthetic autotrophic organisms probably only exist among the bacteria: the soil forms can derive their energy from a considerable

[1] For a recent review of this subject, see J. Franck and H. Gaffron, *Adv. Enzymol.*, 1941, **1**, 199. See also C. B. van Niel, ibid., 1941, **1**, 263.

range of oxidations, such as that of hydrogen to water, hydrogen sulphide to sulphur, and then sulphur to sulphates, ammonia to nitrites and nitrites to nitrates, ferrous iron to ferric iron, and possibly divalent manganese to a more complex ion. Some can obtain their energy by carrying out intermolecular rearrangements such as

$$6KNO_3+5S+2CaCO_3 \rightarrow 3K_2SO_4+2CaSO_4+2CO_2 +3N_2+634 \text{ cals.},$$

which can be performed by the fairly common soil bacteria *Thiobacillus denitrificans*.[1]

Autotrophic organisms can obtain their nitrogen supply from ammonium or nitrate salts, and these are usually the preferred sources; some, perhaps the majority, have difficulty in using most amino acids. No autotrophic bacteria have yet been recognised which can fix atmospheric nitrogen—only some of the autotrophic (and photosynthetic) blue-green algae have this power.

Heterotrophic organisms are usually classified according to the complexity of their necessary nutritional requirements. Most members of the microflora can use simple sugars as their main source of body fuel, but they vary in the types of sugar they can make use of. The majority can use glucose (dextrose) as their primary source, and produce, sometimes only if necessary, enzymes capable of converting a wide range of carbohydrates into this sugar.

Heterotrophic organisms have a wide variety of demands in their food supply. The unspecialised members can obtain all the carbon for their body tissues from simple sugars or fatty acids and their nitrogen from inorganic nitrogen compounds, or, for some bacteria, from gaseous nitrogen. These processes are possible because the organisms can synthesise all the enzymes needed for their life and growth. Other members need more complex food supplies and one can consider that this is due to the organism losing its power to synthesise one or more of these enzymes. The first enzymes that usually cease to be synthesised, as the organism becomes more exacting in its food requirements, fall into two groups: those needed for producing from simple nitrogen sources the whole range of amino acids required for building up the body proteins, and those needed for the organism's respiratory processes. If any of the first group are missing, the organism must be supplied with the essential amino acids, and if any of the second, with the prosthetic groups of the respiratory enzymes which it has lost the power of synthesising. The latter, which are usually members of the vitamin B or yeast "Bios" complex, are only needed in very small quantities, as

[1] R. E. Buchanan and E. I. Fulmer, *Physiology and Biochemistry of Bacteria*, Vol. I, 433, 1928, London.

with vitamins for the human being. In contrast, the amino acids must be supplied in considerably greater quantity if the organism is to reproduce rapidly.

Recently it has been realised that carbon dioxide is also an essential growth factor for many heterotrophic bacteria and fungi. Werkman and Wood[1] have been able to follow a little of the chemistry of this carbon dioxide need by using radioactive carbon, and have obtained evidence that it is needed to convert pyruvic acid—a product of sugar fermentation—into oxalacetic acid, which plays an important role as a hydrogen carrier in the respiratory oxidation of sugars.

This loss of power of synthesising critical substances is scattered over many groups of the microflora in such an erratic way that it has no systematic significance. On the whole, the exactingness of the organism is a reflection of its usual food supply: the more specialised the supply, as, for example, in a well-adapted parasite, the more likely the organism is to have lost the power of synthesising some of the enzymes produced by related organisms utilising a less specialised food supply. It has always been assumed in the past that autotrophic organisms, that is, organisms deriving the carbon of their protoplasm from carbon dioxide, could synthesise all the enzymes and amino acids needed for their growth. This assumption is now known to be false for some of the photosynthetic sulphur bacteria, as some need one or more constituents of the B vitamin complex.[2] Hence there may also be other members of the autotrophic bacteria, in the sense defined above, that need some of the growth-promoting substances—a possibility that has not yet been properly investigated.

All micro-organisms need minerals as well as sources of carbon and nitrogen, though the relative amount needed varies widely with different types. As with plants, potassium and phosphate are needed in considerable quantities, sodium, magnesium, calcium, iron and sulphur often in relatively high quantities, manganese, copper and zinc usually in small quantities by most organisms, whilst molybdenum or vanadium are probably necessary if the organisms are either using nitrate or atmospheric nitrogen as their source of energy.[3] The function of most of these metals is to form part of the prosthetic group of an enzyme; thus, iron and copper are needed for various porphyrins taking part in hydrogen transfer during respiration. *Azotobacter* forms a good example of an organism needing a trace metal only when certain enzymes are required; it can only fix atmospheric nitrogen when supplied with traces of molybdenum or vanadium, but it can grow perfectly well in

[1] For a review of this work, see C. H. Werkman and H. G. Wood, *Adv. Enzymol.*, 1942. **2**, 135; H. A. Krebs, *Ann. Rev. Biochem.*, 1943, **12**, 529.

[2] S. H. Hutner, *J. Bact.*, 1946, **52**, 213.

[3] For a review of the nutrition of fungi, see R. A. Steinberg, *Bot. Rev.*, 1939, **5**, 327.

the absence of this metal if an available supply of ammonium ions is present.

The Respiration of the Microflora: Aerobic and Anaerobic Organisms

All organisms must respire to live, but they have developed different methods of respiration. Some—the obligate aerobes—must have access to free oxygen, whilst others either do not need such access—the facultative anaerobes—or else can respire only in the absence of free oxygen—the obligate anaerobes. Most soil members of the fungi and actinomycetes require conditions of good aeration, and few, if any, members outside the yeasts have been recognised as anaerobes. The soil bacteria, on the other hand, include groups having all degrees of tolerance to progressive oxygen deficiencies, ranging from strict obligate anaerobes through numerous groups relatively insensitive to the oxygen supply to strict obligate aerobes. Little quantitative work has been done on the range of oxygen tensions of the various soil bacterial or even fungal groups, so that one cannot yet classify the bacteria at all accurately by the range of oxygen tensions they can tolerate.

Respiration can be defined as the process of carrying out a chemical reaction which liberates energy with the transfer of part of the energy so liberated into energy available for the vital needs of the organism. The typical sources of energy in the heterotrophic cell are sugars, mainly or perhaps only glucose, and the process of respiration normally consists in breaking down the sugar molecule into simpler ones having smaller total heats of formation. The mechanism of this breakdown can be most simply pictured as transfers of hydrogen atoms from the sugar to a hydrogen acceptor coupled with the residues taking up either water, or the hydroxyl groups from water, when necessary. Thus, the complete oxidation of glucose to carbon dioxide and water involves the tacking on of at least six hydroxyl groups to the six carbon atoms and the removal of at least twenty-four hydrogen atoms, twelve from the sugar itself and twelve from the six water molecules dissociated in the process, and these reactions are brought about by a battery of respiratory enzymes coupled with their appropriate prosthetic groups or co-enzymes that function as hydrogen carriers. Some of these prosthetic groups or co-enzymes contain a member of the vitamin B or yeast "Bios" complex in their constitution, some are metal porphyrins, such as cytochrome, and some are simple 4-carbon dicarboxylic acids, such as oxalacetic.

Oxygen is the final hydrogen acceptor in aerobic respiration, and combined oxygen can play this role under anaerobic conditions. Thus,

many bacteria can reduce nitrates to nitrogen gas or ammonia during respiration, a process involving the transfer of nine hydrogen atoms from the sugar for each molecule of nitrate so reduced to ammonia, whilst other bacteria can reduce sulphates to sulphides, a process involving the transfer of eight hydrogen atoms per molecule of sulphate reduced. Even the oxygen of carbon dioxide can be so utilised, and again eight hydrogen atoms are transferred for each molecule reduced to methane, and this is probably the principal source of the methane produced in anaerobic decompositions.

Oxygen sources are not necessary for anaerobic respiration. The simplest type in which one molecule of sugar is split up into two of lactic acid,

$$C_6H_{12}O_6 \rightarrow 2C_3H_6O_3$$

a reaction brought about by a number of bacteria, involves no transfer of hydrogen at all. But, in general, when an external oxygen supply is not available, respiration proceeds by part of the products of respiration acting as hydrogen acceptors and the remainder as hydrogen donors. The extreme case of this is the typical end-product of the anaerobic fermentation of carbohydrates by a mixed bacterial flora which produces only methane and carbon dioxide,

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4.$$

Here the carbon of the methane has accepted the maximum number of hydrogen atoms a carbon atom can accept, and the carbons of the CO_2 have donated the maximum number. This process need not go to completion, thus alcohol yeast converts glucose into alcohol and carbon dioxide

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

and here only two instead of three of the carbon atoms have lost all their hydrogen.

The outstanding difference between the anaerobic and aerobic fermentation of sugar lies in the energy liberated. Oxidising glucose to carbon dioxide and water liberates about 670 cals. per mol of sugar oxidised; but converting glucose to lactic acid liberates about 18 cals., or to alcohol and carbon dioxide about 30 cals., or to methane and carbon dioxide about 50 cals. per mol of sugar decomposed. Thus anaerobic organisms need to decompose far more organic material to derive a given amount of energy than do aerobic organisms; alternatively, given additions of organic matter will furnish far greater opportunity for increase of microbial activity in aerobic than in anaerobic conditions.

The By-products of Microbial Metabolism: Microbial Excretions

Micro-organisms, like larger organisms, take in food and excrete by-products, which are either products of respiration or components in the food supply that cannot be assimilated. Autotrophic non-photosynthetic organisms must naturally always be excreting the oxidised product of the substrate from which they have derived their energy, whilst heterotrophic organisms must always be excreting carbon dioxide.

Many micro-organisms can multiply in a well-aerated carbohydrate solution and excrete little else except carbon dioxide if the solution contains adequate quantities of ammonia or nitrate. If the conditions are altered—for example, if the nitrogen supply or the degree of aeration is greatly reduced—these same organisms will begin to excrete a variety of energy-rich compounds instead of the fully-oxidised carbon dioxide. Thus, if growth under aerobic conditions is being limited by a reduction in the nitrogen supply, the micro-organisms may keep up their carbohydrate intake but make less efficient use of it. They will then excrete suitable quantities of partially oxidised carbohydrate of relatively high energy content to carry away the energy they have not needed to use.

The excreted products of respiration by heterotrophic organisms growing under limiting conditions consists of two distinct types of compounds: complex carbohydrate gums typically produced by many groups of bacteria under aerobic conditions, and a variety of simple soluble compounds, such as the aliphatic acids from butyric to formic or the derived aldehydes, ketones or alcohols, the simple dibasic acids succinic and oxalic, and the simple hydroxy-acids such as citric, tartaric and lactic—though citric, tartaric and oxalic acids are mainly excreted by certain groups of fungi, such as the Aspergilli.

Micro-organisms usually excrete the nitrogen of originally combined nitrogen that is surplus to their requirements as ammonia under aerobic conditions, though some of the larger may excrete urea or uric acid. But if the aeration is reduced, or anaerobic conditions set in, complex and usually foul-smelling amines are produced along with ammonia, such as the aliphatic amines cadaverine and putrescine and the aromatics indole and skatole.

Micro-organisms may also excrete two quite distinct groups of substances mostly of unknown composition in small quantities. One group, about which very little is known, causes the medium to become "stale", by which is meant that the organism will no longer grow in the medium, even though there is an adequate food supply present. The second group, which may only be a subdivision of the first group,

exerts specific antibiotic activity against a limited group of other organisms.[1] Thus, an active saprophytic microbial population excretes substances which can either kill many pathogenic bacteria and fungi or else prevent them from growing, and this may be the main reason that adequate quantities of decomposable organic matter added to a soil helps to keep in check or reduce the importance of several soil-borne bacterial and fungal diseases. Several of the substances have been isolated and purified, of which penicillin, produced by the fungus *Penicillium notatum*, is the best known.

[1] For a review of this subject, see S. A. Waksman, *Bact. Rev.*, 1941, 5, 231; *Microbia Antagonisms and Antibiotic Substances*, 2nd ed., New York, 1947.

CHAPTER X

THE ORGANISMS COMPOSING THE POPULATION

Bacteria

Historically, bacteria have been far the most important group of soil organisms; they were the first to be studied intensively, and for long were regarded as the only organisms important in normal conditions. Laboratories and departments were set up for their study in most agricultural research institutions, and until recently they have received more attention than all the other soil organisms put together, although they have not yet been shown to play such a predominant role in the vital processes of the soil as is implied by this one-sided development.

THE NUMBER OF BACTERIA IN THE SOIL

Bacteria cannot usually be seen in a natural soil when it is examined under a microscope, but techniques have been developed, based on the use of dyes that either stain living bacteria in the soil, but not the soil colloids or organic matter,[1] or stain the living bacteria so they have a different colour from the organic matter when examined in a fluorescent microscope (see p. 137). These techniques have shown that the bacteria mainly live on the surface of the soil and humus particles, and that they hold on to these surfaces very tightly.

A technique for counting bacterial cells in the soil has, however, been developed by H. G. Thornton and P. H. H. Gray,[2] which has been used fairly extensively, and the results obtained by it are referred to in this book as total cell counts. It is not quite a direct method, as the weight of soil from which the counted population is derived has to be calculated indirectly, and it suffers from the disadvantages that the dye used, erythrosin, stains moribund and newly dead bacteria as well as active ones, and that some actinomycete spores look so like bacteria that they may be counted as such. Thus the method will tend to over-estimate the number of active bacterial cells in the soil.

The method that has normally been used to count the number of bacteria in the soil is the so-called "plating" technique and is much more indirect. A known weight of soil is shaken up with water and some of this suspension, after dilution, is added to a nutrient agar solution and poured on to petri dishes or plates. After incubation the number

[1] H. J. Conn, *New York State Agric. Expt. Sta., Tech. Bull.* No. 64, 1918; S. Winogradsky, *Ann. Inst. Pasteur*, 1925, **39**, 299.

[2] *Proc. Roy. Soc.*, 1934, **115** B, 522.

of bacterial colonies developed on the plate is counted, and so the number present per gm. of soil can be calculated. But the number so calculated can only be considered the number present in the soil if:

(1) each colony on the plate developed from one and only one bacterium;
(2) all the bacteria in the soil sample are brought into suspension;
(3) all the bacteria in the suspension can grow on the nutrient medium used.

None of these conditions, in fact, holds; some bacteria regularly seem to consist of colonies held together by gummy substances, and so are counted as one organism instead of many; some particles of soil and organic matter hold on to bacteria so tightly that dispersion of the bacteria from the substrate is not complete; some bacteria cannot grow in close proximity to others;[1] and no nutrient medium has yet been discovered on which all soil bacteria will develop. Hence, the plating method will under-estimate the number of soil bacteria.

The direct and the plating method thus over- and under-estimate the number of bacteria in the soil, but the difference between the numbers is surprisingly large, as is shown in Table 32,[2] which refers to some arable plots cropped every year with mangolds (Barnfield) and to some grass plots from which one or two hay crops are taken annually.

TABLE 32

Bacterial Numbers in Rothamsted Field Soils

Manuring	pH	Numbers per gm.		Ratio: total count to plate count
		Total cell count (direct method)	Plate count	
Barnfield				
Plot (*Arable, Mangolds*)				
1-O Farmyard manure .	7·6	3,733,000,000	28,860,000	129
4-A Complete minerals + ammonium sulphate	7·2	1,766,000,000	15,100,000	117
8-O No manure . .	8·0	1,005,000,000	7,550,000	133
Park Grass				
13 Farmyard manure .	4·6	2,395,000,000	2,250,000	1064
11-1 Complete minerals + ammonium sulphate	3·8	2,403,000,000	1,350,000	1780
12 No manure . .	5·6	3,041,000,000	7,500,000	405

[1] For a recent discussion of the effect of this factor on the number of bacteria counted, see a series of papers by N. James and M. L. Sutherland, *Canad. J. Res.*, 1940–3, **18** C–**21** C.
[2] Unpublished data of H. G. Thornton and P. H. H. Gray.

The direct method is seen to give over a hundred times as many bacteria on the arable and a thousand times as many on the grass plots as the plating method. All other workers who have used the direct methods of counting have obtained numbers of the order of 10^9 bacteria per gm. of soil whilst their plate counts are usually about a hundred times smaller. The weight of other evidence, such as the rate of respiration of the soil bacteria (p. 196), and the number of bacteria needed to maintain the protozoal population feeding on them (p. 167), give results more in conformity with the higher numbers obtained by the direct count.

The reasons why the plate count gives numbers of bacteria so much too low have not been analysed out in detail, with the consequence that there is no logical justification for concluding that the bacteria isolated from the soil on nutrient media are representative of the soil bacteria as a whole. It is, in fact, commonly assumed that they are, and that the cause of the discrepancy lies more in the other factors already mentioned than in the inability of a substantial majority of the bacteria being able to grow on any of the less selective media used, but this possibility cannot yet be ruled out.

The figures given in Table 32 can be used to estimate the weight of the bacteria in an acre of soil. The typical soil bacteria are very small. Their mean volume is not known, but is probably about $1\,\mu^3$, or 10^{-12} c.cm., so that their mean weight is about 10^{-23} gm. If there are three thousand million bacteria per gm. of soil, they will weigh 3 mgm. per gm. of soil or, assuming they average this number throughout the top six inches of soil, and six inches of soil weighs 1,000 tons per acre, they will weigh about 3 tons per acre live weight or 0·6 ton dry weight; say 1,300 lb. dry weight containing 130 lb. of nitrogen. This soil would probably contain about 5 per cent of organic matter by dry weight, so that there would be about 50 tons of dry organic matter per acre of soil, of which the bacteria would only constitute about 1 per cent.

THE TYPES OF SOIL BACTERIA

The prime difficulty in the classification of the soil bacteria can now be appreciated. The only certain way the bacteria can be classified is by their behaviour on different nutrient media, but it is possible that the majority of the types of bacteria present in the soil have never yet been grown on any medium. And in all the discussions of bacterial classification which involve platings this limitation must be remembered.

The soil bacteria can be classified by their nutritional requirements. The division between autotrophs and heterotrophs has already been mentioned (p. 138). The heterotrophs can be classified according to

the complexity of their nutritional requirements, as has been attempted by Lochhead and his co-workers.[1] They isolate soil bacteria on as non-selective a medium as possible, and then test the proportion that can grow on media of increasing simplicity. Thus they have suggested seven groups as follows:

1. Those growing in a simple glucose-nitrate medium containing mineral salts.
2. Those that can only grow when ten amino acids are added to this medium.
3. Those that can only grow when cysteine and seven growth factors (aneurin, biotin, etc.) are added.
4. Those needing both the amino acids and the growth factors.
5. Those needing yeast extract.
6. Those needing soil extract.
7. Those needing both yeast and soil extract.

They found that fertile soils contain a greater proportion of bacteria with complex requirements, i.e. belonging to groups 5, 6 and 7, than infertile; that the soil extract from a fertile soil has a greater growth promoting power than from an infertile; and that the bacteria in the immediate vicinity of plant roots fall more into groups 2, 3 and 4 than into the more complex groups.[2] H. Katznelson and F. E. Chase[3] found that adding generous dressings of farmyard manure to a soil increased the proportion of bacteria having complex growth requirements at the expense of those having very simple ones, and V. Garcia, working with soils from some of the Rothamsted plots, confirmed this result and found that soils which had large dressings of fertilisers had the same distribution of bacterial types as the unmanured. This classification can, however, be criticised on the grounds that it measures properties connected with the environment of the soil, rather than with the inherent properties of the bacterial population, for some bacteria which appear to have complex growth requirements can be trained to produce the enzymes necessary to make for themselves some at least of these requirements.

The morphological classification of soil bacteria is also difficult, as some groups can have several forms. A usual classification for the soil bacteria has been into six groups:

1. Small cocci, usually about 0·5 μ in diameter.
2. Short straight rods, about 0·5 μ in diameter and 1–3 μ long; the shorter often being called coccoid rods.

[1] A. G. Lochhead and F. E. Chase, *Soil Sci.*, 1943, **55**, 185. An earlier classification on these same principles was given by P. M. West and A. G. Lochhead, ibid., 1940, **50**, 409.

[2] P. M. West and A. G. Lochhead, *Canad. J. Res.*, 1940, **18** C, 129. See also H. Katznelson and L. T. Richardson, ibid., 1943, **21** C, 249.

[3] *Soil Sci.*, 1944, **58**, 473.

3. Short curved rods—the Vibrios.
4. Long rods.
5. Rods sometimes showing branching.
6. Thin flexible rods, with very thin cell walls, usually under 0·5 μ in diameter and 2–10 μ long.

There also appear to be some very small bacteria in the soil, existing as cocci or coccoid rods with diameters down to 0·15 μ, but some of these may be stages in the life of larger bacteria.[1] Groups 4 and 5 are usually Gram-positive bacteria, and are at the present time assigned to the *Proactinomycetes*, now called *Nocardia* and classified with the actinomycetes, and to the *Corynebacteria* and *Mycobacteria*, which are organisms now considered to be intermediate between true bacteria and actinomycetes.[2] Group 6 are Gram-negative and include the soil *Cytophaga* and *Sporocytophaga* groups and any other *Myxobacteria* present. This classification is of only limited value, unless its limitations are clearly recognised, for many organisms classified in groups 4, 5 and 6 also exist as cocci and small rods, and many will, in fact, take this form when growing in conditions of limited food supply such as exist in normal soils. Under these conditions they will be indistinguishable visually from members of groups 1 and 2, with the consequence that many of the short and coccoid rods seen in the soil either on Cholodny slides or by direct microscopic observation will appear as members of groups 4, 5 or 6 when grown on plates. Further, many of the long rods will only show branching if grown under special culture conditions, so that no one medium can pick out all the bacteria having this property.

There is no necessary correlation between these two methods of classification; thus bacteria existing as short rods may be found in all the nutrition groups. This is an example of the general statement already made for the microflora that the loss of power to synthesise essential growth substances has little correlation with systematic classification.

Direct observation of the bacterial flora in soils shows up the overwhelming predominance of short and coccoid rods in most soils, though cocci, which may principally be actinomycete spores, predominate in a few. Clumps of cocci or coccoid rods can sometimes be seen embedded in slime and some of the organisms are surrounded by gummy capsules. Large rods are relatively rare and occur either in chains or singly. Large cocci sometimes occur, commonly in groups of two, three or four together in a colony. Plate VII shows some typical bacterial colonies of these kinds.

The plating technique, particularly if a nutrient-poor non-selective

[1] See P. P. Laidlaw and W. J. Elford, *Proc. Roy. Soc.*, 1936, **120** B, 292, for a possible example of small soil bacteria in sewage.

[2] *Bergey's Manual of Determinative Bacteriology*, 5th ed., Baltimore, 1948.

medium is used, picks out, as Conn showed several years ago, many small slow-growing short rods. C. B. Taylor and A. G. Lochhead,[1] for example, found about 90 per cent of all the bacteria picked out were short rods, which Lochhead[2] and L. E. Topping[3] consider to belong mainly to the *Corynebacteria*, *Mycobacteria* and *Nocardia*, though H. J. Conn and I. Dimmick[4] consider that the first two differ too much from these pathogens of these names and suggest they be put in a new genus *Arthrobacter*. Conn considers there is a second main group of these bacteria related to legume nodule bacteria,[5] and he suggests these be put into a second new genus *Agrobacter*.[6] This would include the common soil species that has been known *Achromobacter radiobacter* as well as *Phytomonas tumifaciens*, a common soil bacteria that can produce crown galls on the roots of some plants. Many of the common strains are characterised by great variability of morphology, depending on the nutrient medium in which they are growing; by their ability to grow on a very wide range of nutrients, although many need traces of yeast or soil extract for growth; and by low metabolic activity, that is, they develop best when they are growing slowly in media only containing low concentrations of nutrients. Under these conditions H. J. Conn and M. A. Darrow[7] showed that they are extremely efficient users of sugars, utilising about 50 to 60 per cent for CO_2 production, 25 to 30 per cent for building into their body tissue, and excreting only about 15 per cent, and also that they build into their protoplasm about 70 to 80 per cent of the nitrogen they consume.

S. Winogradsky,[8] using his direct microscopic method of observing the soil bacteria, suggested the name *autochthonous*, that is, indigenous, for this common microflora of short and coccoid rods. He considered that this population characterises soils containing no easily fermentable material, and he pictured it feeding on the soil humus. Conn and Lochhead have developed this idea by showing that many members of this population are characterised by low biochemical activity, some having very complex nutritional requirements, and others great adaptability.

Winogradsky contrasted this autochthonous population with the dormant *zymogenous* group that springs into prominence whenever fermentable material is added to the soil, but which sinks down again as soon as it is exhausted. He pictured this population as composed of long rods and spore-formers. The existence of this separate population is, however, doubtful. Taylor and Lochhead[9] found that the addition of 15 tons per acre of farmyard manure did not change the

[1] *Canad. J. Res.*, 1938, **16** C, 162. [2] *Proc. 3rd Int. Cong. Microbiol.*, New York, 1939, 686.
[3] *Zbl. Bakt.* II, 1937, **97**, 289; 1938, **98**, 193. [4] *J. Bact.*, 1947, **54**, 291.
[5] *Bact. Rev.*, 1948, **12**, 257. [6] *J. Bact.*, 1942, **44**, 353. [7] *Soil Sci.*, 1935, **39**, 95.
[8] *C.R.*, 1924, **178**, 1236. [9] *Canad. J. Res.*, 1938, **16** C, 162.

types of bacteria in the soil, but only increased their number, and Cutler and Crump[1] found that Plot 2 on Broadbalk Field at Rothamsted, which has had a dressing of 14 tons of farmyard manure per acre most years since 1843, carried the same dominant bacterial species as Plot 3, which has been unmanured all this time. Cutler and Crump, in their very detailed studies, were able to show, however, that different fields carried different predominant populations; thus, Broadbalk Field, which carries a wheat crop nearly every year, has a different population from Barnfield, which carries mangolds annually, suggesting that the crop has a greater influence than the manure on the population (see p. 158).

There are also bacteria in the soil that feed on some of the common species of soil bacteria. They do this by excreting a substance that dissolves, or lyses, the bacterial membrane that encloses the living protoplasm and then absorbing the liquid cell contents.[2] These bacteria belong to the *Myxobacteria*, or slime bacteria. They were originally considered to feed on animal dungs, as that was the only food on which they could be made to grow and form the characteristic fruiting bodies by which they are recognised, but it is now known that their food is either living or dead bacterial cells and possibly other micro-organisms. Although many species are known, soils only seem to contain very few. Thus, B. N. Singh[3] only found three species commonly present and a fourth more rarely. He found them in all the British arable soils and in about two-thirds of the pasture soils be examined, and in the single soil in which he tried to count them there were between 2,000 and 80,000 per gm.

These higher predaceous bacteria are not the only members of the myxobacteria present in the soil, as many of the cellulose and chitin[4] decomposers, such as the *Sporocytophagas* and the *Cytophagas*, belong to this group,[5] but it has not yet been conclusively shown that they can ever form the characteristic fruiting bodies of the predaceous species.

THE FLUCTUATIONS IN THE NUMBER OF SOIL BACTERIA

The numbers of bacteria in the soil are never stationary. D. W. Cutler, L. M. Crump and H. Sandon,[6] as long ago as 1920–1, showed the numbers counted by their plating technique fluctuated from day to day during the course of the year, and C. B. Taylor[7] showed these fluctuations occurred from hour to hour, whether they were counted by Thornton and Gray's total cell count method, or were counted on

[1] Private communication from Miss L. M. Crump.

[2] See, for example, J. M. Beebe, *Iowa St. Coll., J. Sci.*, 1941, **15**, 307, 319; A. E. Oxford and B. N. Singh, *Nature*, 1946, **158**, 745.

[3] *J. Gen. Microbiol.*, 1947, **1**, 1.

[4] For a review of this subject, see R. Y. Stanier. *Bact. Rev.*, 1942, **6**, 143.

[5] R. Y. Stanier, *J. Bact.*, 1947, **53**, 297.

[6] *Phil. Trans.*, 1922, **211 B**, 317.

[7] *Proc. Roy. Soc.*, 1936, **119 B**, 269.

mannite or soil extract plates. He found that the fluctuations in numbers determined by these three methods were uncorrelated, as is shown in Fig. 15,[1] where the plate count was made on soil extract agar, suggesting that the fluctuation in total numbers is made up of a series of fluctuations occurring independently in different groups of bacteria.

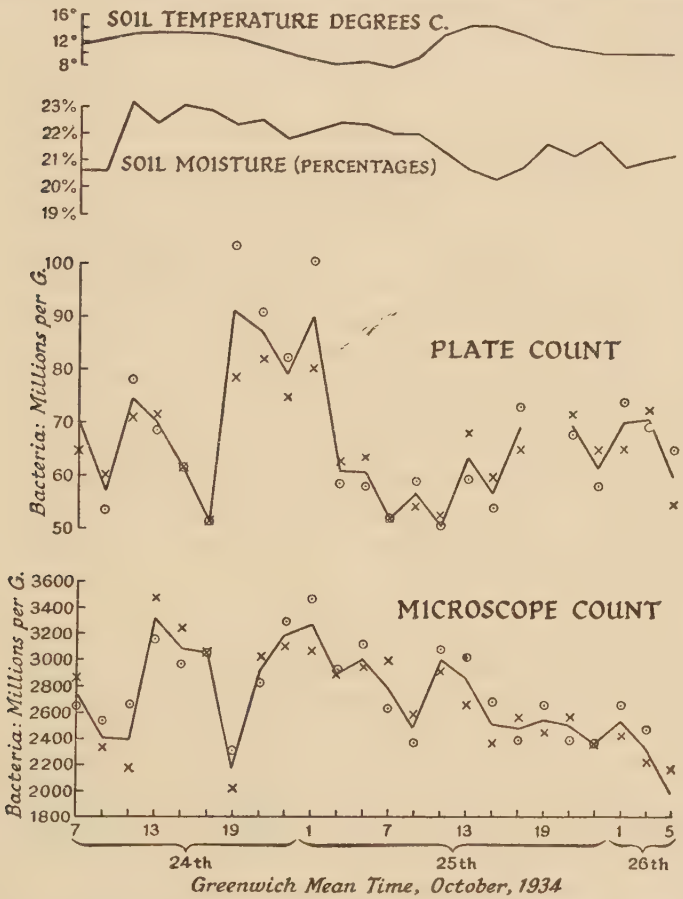


FIG. 15. Total cell and plate counts of bacteria from two-hourly samples of fallow garden plot soil.

Note.—In the curves shown here, the dots and crosses represent numbers found in duplicate samples; all curves show mean values.

The causes of these variations are not known, though presumably they are related in part to the protozoal activity in the soil. Further, Taylor has shown that these variations occur even if the soils are kept at a constant temperature and moisture content.

[1] Taken from H. G. Thornton and C. B. Taylor, *Trans. 3rd Int. Cong. Soil Sci.*, Oxford, 1935, **1**, 175.

Bacteriophages[1]

Some groups of bacteria can be attacked by bacteriophages, which appear to be bodies similar to plant and animal viruses. Their typical form of attack is to cause a sudden lysis, or dissolving, of the outer bacterial membrane, which allows the contents of the bacterial cell to diffuse into the liquid medium. In this property, bacteriophages resemble the bacteriocidal substances excreted by other micro-organisms. Where the phages differ from these substances is that they multiply during this lysis, and in fact the only way they can be multiplied is by growing them on susceptible strains of bacteria. It has also been claimed that some phages can grow on bacteria without lysing them, that is, they appear to be well-adjusted parasites. The method of multiplication or nutrition of the phage is unknown, and so is its seat of action, whether on or inside the bacterial membrane.

Phages have been recognised attacking species of bacteria belonging to all the main widely distributed groups, and also some species of actinomycetes, but it is still doubtful whether any have been found attacking fungi. The phages of greatest practical interest from the point of view of crop growth are those attacking the nodule bacteria, but very little is yet known about their distribution in nature, nor even how often they are of any importance in causing "clover sickness" or a reduction in the nitrogen-fixing ability or number of nodule bacteria in soil (see p. 486).

Actinomycetes

These organisms form a transition between the bacteria and the fungi, and on the bacterial side there is a series of organisms ranging in form from true bacteria, through the *Mycobacteria* and the *Nocardia* to true actinomycetes, the soil forms of which are now classified in the genera *Streptomyces* and *Micromonospora*;[2] and it is probable that there is this same continuity between actinomycetes and simple filamentous fungi. Further, in the soil some actinomycete filaments look like fungal mycelia and some of their spores like bacteria, though their spores typically differ from bacterial by having a waxy surface that does not readily wet. Thus, when a soil suspension is being made, many of them will float on the surface of the suspension, thus preventing any accurate count of their numbers by the usual dilution techniques.

Actinomycetes form very fine, often much-branched, hyphae when growing, and these hyphae may break up into spores, either by the

[1] For a recent review, see M. Delbrück, *Adv. Enzymol.*, 1942, **2**, 1, from which the substance of this account is taken.

[2] S. A. Waksman and A. T. Henrici, *J. Bact.*, 1943, **46**, 337; D. Erikson, *Ann. Rev. Microbiol.*, 1949, **3**, 23.

tip of the hypha producing one or two spores or else by a length of hypha, often a length of hypha twisted into a coil, breaking up into a line of spores. In the soil these characteristic hyphal coils are only produced if they have free access to air, so that they are typically produced in the surface pores of a moist soil which are shaded from the direct sun.[1] The actinomycetes in the soil may also be responsible for the characteristic smell of newly ploughed land, for when they are sporing in pure cultures, they give off odours that vary from earthy to musty.

The soil actinomycetes are nutritionally a very adaptable group; they are probably without exception heterotrophic, and can use a wide range of carbon and nitrogen compounds, such as celluloses, hemicelluloses, proteins and possibly lignin.[2] They do not seem to need any growth-promoting substances. No actinomycete has been shown to fix atmospheric nitrogen, though O. von Plotho[3] has made this claim for *A. alni*, which is said to form nodules on alder and to be capable of fixing nitrogen both in the nodule and in pure culture. Only a few actinomycetes are parasitic on plants and then usually on their roots.

The activity of actinomycetes in a soil cannot yet be determined. Direct methods of observation, such as those of Jones and Mollison, should be able to be used to give estimates of the length of actinomycete hyphae in soils, in so far as they can be distinguished from fungal hyphae. H. L. Jensen[4] has, however, made estimates of their relative activities in different soils by assuming it is proportional to the density of their hyphae on Cholodny slides buried in the soil. Actinomycetes, however, often develop extensively on plates used to count the number of bacteria in the soil, but these probably usually develop from spores. As already mentioned, since actinomycete spores are waxy and difficult to wet, the plating technique usually seriously under-estimates the number present in the soil.

Soil actinomycetes are typically aerobic organisms and, like the fungi, are commoner in dry than wet soils. They are also commoner in warm than cool soils; thus Jensen found that they can be the dominant members of the microflora at temperatures around 28° C. if the water supply is restricted, and many of them can thrive in the aerated parts of a compost heap even when the temperature reaches 60° to 65° C. They also appear to be very active under pastures, and may be the dominant micro-organisms in the surface layers of grassland in this country if the soil is not too acid.

[1] D. Erikson, *J. Gen. Microbiol.*, 1947, **1**, 45.
[2] S. A. Waksman, *Antonie van Leeuwenh.*, 1947, **12**, 49.
[3] *Arch. Mikrobiol.*, 1941, **12**, 1.
[4] *Proc. Linn. Soc., N.S.W.*, 1943, **68**, 67.

Fungi

The fungi form the third of the three great groups of the soil microflora, and whether they, the actinomycetes or the bacteria predominate in a soil depends on local conditions. Soil fungi in most normal arable soils are too small to be seen either with the naked eye or with a magnifying glass, although they can often be seen growing on the surface of dead leaves and other plant debris. Fungal filaments can sometimes be seen in arable soils using Kubiena's microscope technique, and they often appear on Cholodny slides buried in the soil. Jones and Mollison were also able to see fungal mycelia in normal arable soils, using their direct staining technique, but considered that much of the mycelium was either dead or inactive. They found more pieces of mycelium than spores, though there may be more spores than active pieces of mycelium. Jones has also observed that as fungal mycelium grows, the active dark staining part of the fungus keeps in the vicinity of the growing points and leaves light staining and presumably fairly empty pieces of mycelium behind. Fungi are certainly predominant in some raw humus or mor soils,[1] where some are usually visible to the naked eye, and they may constitute an important part of the zymogenous microflora[2] of normal agricultural soils, but the extent of their contribution to the autochthonous flora of these soils is still debatable.

The soil fungi that have so far been recognised as soil inhabitants all belong to the group that form filaments or mycelia, with the exception of some organisms belonging to the Myxomycetes, or slime fungi, and a few yeast-like organisms. They belong mainly to the Phycomycetes, which have branched unseptate mycelia, and to either the Moniliaceae, a group of Fungi Imperfecti, or, where the perfect form is known, to a related group in the Ascomycetes, which have branched septate mycelia. Basidiomycetes certainly occur in some soils, particularly forest and grassland soils, though whether they are present in appreciable numbers in old arable soils is uncertain. The soil Phycomycetes mainly belong to the Saprolegniales, to the genus *Pythium* and to the Mucoraceae, including the genera *Mucor*, *Rhizopus* and *Zygorrhynchus*. The soil Moniliaceae belong mainly to the genera *Trichoderma*, *Aspergillus*, *Penicillium*, *Cephalosporium* and *Fusarium*.[3] The soil Basidiomycetes belong to the Hymenomycetes, or mushroom-like, and the Gasteromycetes, or puffball-like fungi. They appear to be of most importance in forest soils, where they include many species which

[1] L. G. Romell, *Cornell (N.Y.) Agric. Expt. Sta., Mem.* 170, 1935.

[2] W. Kubiena and C. E. Renn, *Zbl. Bakt.* II, 1935, **91**, 267; H. L. Jensen, *Proc. Linn. Soc., N.S.W.*, 1934, **59**, 200.

[3] For a description of typical soil fungi, see J. C. Gilman and E. V. Abbott, *Iowa St. Coll. J. Sci.*, 1927, **1**, 225; J. C. Gilman, *A Manual of Soil Fungi*, Ames, 1945; A. Niethammer, *Die Mikroskopischen Bodenpilze*, 's Gravenhage, 1937.

can attack lignin strongly and others which form mycorrhiza on the tree roots (see p. 220). Fungi of these groups also give the "fairy rings"[1] of old pastures.

Very little is known about the geographical distribution of these various types of fungi, though S. A. Waksman's[2] generalisation, made in 1917, is still probably valid that the *Mucorales* and *Penicillia* are characteristic of cooler and the *Aspergilli* of warmer climates, whilst *Trichodermae* have their greatest development in forest soils.

Our knowledge of the soil fungi is still very limited, due to a lack of suitable techniques for studying them. They can only be isolated for identification and study if they can be grown in a suitable medium outside the soil, and one does not know *a priori* what range of media is necessary. Thus, our knowledge of the soil Basidiomycetes is still severely limited because they will either not grow at all, or only very slowly on laboratory culture media, and then without forming their fruiting bodies. Again, only recently has the presence of fungi predaceous on amoebae and nematodes been recognised in the soil, and this property can obviously only be recognised in the laboratory if they are grown in a medium containing suitable organisms for them to prey on.[3]

It is not always possible to decide if a fungus is a soil-inhabiting fungus in Waksman's terminology, that is, one that can live and grow in the highly competitive environment of the soil, or is just resting in the soil and waiting the opportunity to attack a plant—a soil-invading fungus. The latter fungi are usually specialised parasites, only able to attack a limited range of plants, which they enter through the root system. Many of the former fungi are unspecialised parasites with a wide range of host plants, but they are usually only capable of entering the plant, so becoming parasitic, either if it has already been attacked by a primary invader or if it has lost vigour for some other reason.[4] Waksman was one of the first to realise the importance of this problem of separating out the soil inhabiters from what he called the soil invaders. He assumed that if a fungus had a very wide geographical distribution it was a soil inhabiter, and if only a local distribution—usually correlated with past or present vegetation—it was a soil invader. O. A. Reinking's work on the distribution of various Fusaria in tropical soils has illustrated the value of this concept.[5]

[1] For a list of these fungi, see H. L. Shantz and R. L. Piemeisel, *J. Agric. Res.*, 1917, **11**, 191. For a description of various British types, see J. S. B. Elliott, *Ann. Appl. Biol.*, 1926, **13**, 277. [2] *Soil Sci.*, 1917, **3**, 565. [3] C. Drechsler, *Biol. Rev.*, 1941, **16**, 265.

[4] For a discussion of soil-borne fungi causing root diseases on plants, see S. D. Garrett's Monograph, *Root Disease Fungi*, Waltham, Mass., 1944.

[5] *Zbl. Bakt.* II, 1934, **89**, 502; **90**, 4; 1935, **91**, 243. For another example of a soil inhabiting Fusarium that can be parasitic on wheat seedlings, see T. S. Sadasivan, *Ann. Appl. Biol.*, 1939, **26**, 497.

Great difficulties arise, which have only partially been overcome, when any attempt is made to estimate quantitatively the activity of the soil fungi. No methods have yet been developed for estimating the contribution of the fungi to the CO_2-production in the soil, and only recently have dyes been found able to stain the fungal mycelia in a soil sufficiently distinctively for them to be readily recognised.[1] H. L. Jensen has,[2] however, devised a method of utilising the Cholodny slide technique for comparing the relative bulk of fungal tissue in different soils based on the assumption that it is proportional to the relative abundance of the tissue on the slides. Estimates have been made of the number of fungi present in the soil by using the plating technique with suitable media, but the results have only limited value because the concept of what constitutes a fungus individual is not clear. Thus, in some species all the spores and every separate piece of mycelium grow rapidly on the medium and so are counted as separate individuals, in other species only the spores or the pieces of mycelium grow rapidly, whilst in others the fungus either grows so slowly on the medium that it is swamped by its rapidly growing neighbours, or it cannot grow at all, and in either case is not counted.

The numbers of fungi counted by these plating methods vary from a few thousand to over one million per gm. of soil,[3] and the technique can show that the species present depend on the soil conditions. Thus, J. Singh,[4] working on the permanent wheat and mangold plots at Rothamsted, found that the crop affected the species of fungi present, but the manurial treatments, even those involving dressings of farmyard manure, did not. Thus *Monilia* was common on both fields, *Fusaria* were more common on the wheat field and *Penicillia* and *Dematia* on the mangold field.

The soil fungi are probably all heterotrophic, as no species has yet been shown to be truly autotrophic, though a fungus has been found that can oxidise manganese salts to manganese dioxide; but it has not yet been grown in a medium free from organic matter.[5] The different species have a very wide range of food requirements,[6] ranging from those which can utilise many simple carbohydrates, alcohols and organic acids, sometimes together with carbon dioxide as their sole source of carbon, and ammonia or nitrate as their source of nitrogen,

[1] See, for example, P. C. O. Jones and J. E. Mollison, *J. Gen. Microbiol.*, 1948, **2**, 54.

[2] *Proc. Linn. Soc., N.S.W.*, 1935, **60**, 145.

[3] W. B. Brierley, S. T. Jewson and M. Brierley, *Proc. 1st Int. Cong. Soil Sci.*, Washington, 1927, **3**, 48; H. L. Jensen, *Proc. Linn. Soc., N.S.W.*, 1934, **59**, 101.

[4] *Ann. Appl. Biol.*, 1937, **24**, 154.

[5] I am indebted to Dr. D. M. Webley for the information about this fungus, which he isolated from a Rothamsted soil. See also M. W. Beijerinck, *Fol. Microbiol.*, 1913, **2**, 123.

[6] For a review on recent work on the nutrition of fungi, see R. A. Steinberg, *Bot. Rev.*, 1939, **5**, 327.

through those that need a group of amino acids or of accessory growth substances, such as the B group of vitamins, to those which can only grow in competition with the general soil population as parasites on living plants or as parasites or predators on living animals. Probably all fungi need to be supplied with either inorganic nitrogen salts or organic nitrogen compounds for their source of nitrogen, though there may be fungi that have some power to utilise atmospheric nitrogen either as their sole or subsidiary source of nitrogen, but, as noted on p. 305, this whole subject is in need of reinvestigation with modern techniques.

The saprophytic fungi can be very efficient converters of food into microbial tissues; some can synthesise 30 to 50 per cent of thecarbon in the food into their cell substance,[1] which is higher than the corresponding figure for most bacteria when growing in the presence of an abundant food supply, though possibly not so much higher than for the autochthonous flora, since H. J. Conn and M. A. Darrow[2] found that typical members of this flora could synthesise 30 per cent of the carbon in the ingested sugar into their own tissues when the sugar concentration was low. This high efficiency of conversion has the corollary that rapidly growing fungi make very high demands on the available nitrogen of the soil, much of which is only released very slowly in a form available to plants.

The filamentous fungi generally need aerobic conditions to flourish, though they do not need aerobic conditions all along their filaments: they are capable of sending filaments into poorly-aerated pockets of soil, but only if much of the filaments are growing in well-aerated conditions, and only these well-aerated parts ever produce spores. They are thus more common near the surface of the soil than lower down, and H. L. Jensen,[3] in Denmark, found them more common on light well-aerated soils than in heavier, as shown in Table 33. They can tolerate a wide *p*H range, though, typically, they flourish under extremely acid conditions such as occur in heaths and acid forests.[4]

The larger Hymenomycetes and Gasteromycetes, so typical of the surface of forest soils, nearly all need complex growth factors for active growth,[5] and can only make their fruiting bodies when they are growing in optimum conditions of an adequate moisture supply, fairly high temperatures and a good supply of available nitrogen—conditions that commonly only occur in autumn in these soils.[6]

[1] S. A. Waksman, *Principles of Soil Microbiology*, 2nd ed., 1931, London, p. 244.
[2] *Soil Sci.*, 1935, **39**, 95.
[3] *Soil Sci.*, 1931, **31**, 123.
[4] *J. Agric. Sci.*, 1931, **21**, 38.
[5] See, for example, E. Melin, *Symb. Bot. Upsaliens.*, 1946, No. 8.
[6] J. Grainger, *Trans. Brit. Mycol. Soc.*, 1946, **29**, 52.

TABLE 33

Effect of $CaCO_3$ on Numbers of Fungi, Actinomycetes and Bacteria in Soils as found by Plating Methods

Number per gram of soil

	Heath soil				Sand soil				Light loam			
	pH	Fungi, thousands	Bacteria + Actinomycetes, millions	Actinomycetes, per cent	pH	Fungi, thousands	Bacteria + Actinomycetes, millions	Actinomycetes, per cent	pH	Fungi, thousands	Bacteria + Actinomycetes, millions	Actinomycetes, per cent
Untreated soil	3·7	610	0·84	0	4·7	341	5	61	5·8	127	8	36
$CaCO_3$ added	7·5	393	398	21	7·6	365	23	35	7·6	120	17	20

Algae

The soil algae are microscopic chlorophyll-containing organisms, and belong mainly to the Cyanophyceae (Myxophyceae) or blue-green, the Xanthophyceae or yellow-green, the Bacillariaceae or diatoms and the Chlorophyceae or green algae. The soil forms typically comprise smaller and simpler species than the aquatic forms, and consist either of species which only occur as small organisms or of dwarfed forms of species that can occur as large organisms.[1] The morphology of the soil forms is also simple: they occur either as simple unicellular organisms or simple filaments or colonies. Many of the soil algae have their cell walls covered with a thick layer of a gummy substance; whilst the cell walls of most diatoms are partially silicified.

The soil algae are found not only on the surface and just under the surface, where sunlight or diffused light may be able to penetrate, but also several inches below the surface where no light can penetrate. The surface and immediate sub-surface forms presumably function as green plants, converting the carbon dioxide of the air into their protoplasm and taking up nitrates or ammonia from the soil. What activity those in the dark can display is still undecided. The earlier workers, such as B. M. Bristol Roach,[2] considered that the algae grew heterotrophically below the soil surface, and she found on arable land that there were often more algae at a depth of four inches than at the surface.

[1] See J. W. G. Lund, *New Phytol.*, 1945, **44**, 196, and 1946, **45**, 56, for a recent discussion on the validity and interpretation of this generalisation for the diatoms; he gives the references to the earlier work on which it was based.

[2] *J. Agric. Sci.*, 1927, **17**, 563.

The common soil algae can certainly grow in the dark on a medium containing sugars, but it is very doubtful how far the algae could compete with the bacteria or fungi for such readily assimilable compounds which are nearly always in extremely short supply. J. L. Stokes[1] showed in some laboratory experiments that adding such substances as sugars, lucerne meal, straw or manure to a soil, and incubating in the dark, increased the numbers of bacteria very considerably, but had little effect on the numbers of algae. Several years before this, F. E. Fritsch[2] had suggested that the majority of these algae occurring beneath the zone of light penetration had either been washed down to these lower layers or had been carried down by tillage operation or by the soil fauna.

The relative importance of the different groups of algae in different soils has not yet been worked out. It seems to be generally true that in temperate soils green algae and diatoms are probably about equally common and the blue-green less common, though the relative differences between the blue-green and the rest may be larger in infertile than in fertile soils.[3] In many tropical soils, however, the blue-green appear to be the dominant algal group.

Algae develop most readily in damp soils exposed to the sun, hence usually have their maximum development in spring and autumn when the soil is damp, the sun not too hot and other vegetation rather dying down. They develop most freely on fertile soils well supplied with bases, available phosphates and nitrates, and tend to be sparse on light, infertile, acid soils.[4] Bristol Roach at Rothamsted found that generous dressings of farmyard manure increased their number compared with unmanured soil, though Stokes in New Jersey found that farmyard manure had a depressing effect on algal numbers. The explanation of the difference between the two centres may be due to the much greater degree of nitrogen starvation on the Rothamsted than on the New Jersey control soil, so that the algae on the Rothamsted manured soil may only have been responding to the available nitrogen in the manure. Lund[5] has also found that the green algae form the dominant group of algae in acid soils, but as the soils become more neutral the blue-green algae and the diatoms become relatively as important, and on fertile soils the blue-green may be the dominant group.

The numbers of algae occurring in a gram of soil vary widely according to conditions. Both Bristol Roach and Stokes record numbers up to 100,000 or 200,000, though up to 800,000 per gm. have been

[1] *Soil Sci.*, 1940, **49**, 171.
[2] *Essays in Geobotany in Honor of W. A. Setchell*, p. 195, Univ. of California Press, 1936.
[3] E. W. Fenton, *Trans. Bot. Soc. Edinburgh*, 1943, **33**, 407.
[4] J. W. G. Lund, *New Phytol.*, 1945, **44**, 196; 1946, **45**, 56.
[5] *New Phytol.*, 1947, **46**, 35.

reported in some Utah[1] and Hungarian[2] soils and up to 3,000,000 in some Danish soils.[3] One can make a rough estimate of the volume of this algal protoplasm as it is a reasonable approximation to take the volume of each alga equal to a sphere of 10 μ radius, and this gives volumes of the order of a few tenths of a cubic millimetre per gramme of soil.

The soil algae probably affect plant growth in four ways: they may add some organic matter to the soil, help bind the soil particles on the surface together, improve the aeration of swamp soils and fix atmospheric nitrogen.

The amount, and the significance, of the organic matter algae add to normal soils is not known, but the part played by this organic matter in recolonising burnt or barren land is fundamental. F. E. Fritsch and E. J. Salisbury[4] found slimy green algae as the primary colonisers of burnt-over heathland in England. M. Traub[5] found blue-green algae were the primary colonisers on the barren mineral layer created by the eruption of Krakatoa in 1883; W. E. Booth[6] found them growing actively on bare eroded soil in Oklahoma, and he made the interesting additional observation that this algal film over the surface did not reduce the infiltration capacity of the soil;[7] and N. N. Bolyshev and T. I. Evdokimova[8] found they produced the slippery surface crust or takyr on saline lake-bed soils in central Asia.

Algae may help the aeration of swamp soils by converting the dissolved carbon dioxide in the water to dissolved oxygen. U. Brizi[9] observed that *brusone* disease of marsh rice, which he attributed to inadequate aeration, did not appear if algae developed plentifully on the surface of the marsh (see also p. 253). Recently H. B. Engle and J. E. McMurtrey[10] have shown that adding green algae to water cultures in which tobacco is growing improves the aeration of the solution if the culture is kept in the light, resulting not only in an improved growth of the tobacco plants, but also in an increased immunity of their roots to fungal infections.

Some of the blue-green algae of the family Nostococcaceae, including members of the genera *Nostoc*, *Anabaena*, *Aulosira* and *Cylindrospermum*, have been shown to possess the power of fixing nitrogen from the

[1] T. L. Martin, *Proc. 3rd Int. Cong. Microbiol.*, New York, 1940, 697.
[2] D. Fehér, *Arch. Mikrobiol.*, 1936, **7**, 439.
[3] J. B. Petersen, *Dansk. bot. Archiv.*, 1935, **8**, Nr. 9.
[4] *New Phytol.*, 1915, **14**, 116.
[5] *Ann. Jard. Bot. Buitenzorg*, 1888, **7**, 221. This has since been somewhat qualified by C. A. Barker, *The Problem of Krakatoa as seen by a Botanist*, The Hague, 1930.
[6] *Ecology*, 1941, **22**, 38.
[7] *Pedology*, 1944, Nos. 7–8, 345.
[8] This observation has been confirmed for the algal crust on desert soils in Arizona by J. E. Fletcher and W. P. Martin, *Ecology*, 1948, **29**, 95.
[9] *Ann. Instit. Agrar., Milan*, 1906, **6**, 59; 1908, **7**, 107. See also the work of W. H. Harrison and P. A. S. Aiyer, which is described on p. 253.
[10] *J. Agric. Res.*, 1940, **60**, 487.

atmosphere,[1] and thus have simpler food requirements than any other organisms, since they can obtain both their carbon and nitrogen from the air. This power of nitrogen fixation is not dependent on light, for these algae can fix nitrogen readily in the dark if supplied with sugar, but it is lost if the algae are supplied with nitrates, ammonia or asparagine. They need, however, small quantities of molybdenum,[2] and there seems little reason to doubt that the enzyme system responsible is similar to that of *Azotobacter*. Allison and Singh found the optimum *p*H for fixation was on the alkaline side of neutrality, from about *p*H 7–8·5, and fixation probably occurred in the range *p*H 6–9.

These nitrogen-fixing blue-green algae are probably of great importance in rice culture. It has always been rather difficult to understand how many tropical rice soils can carry rice crops almost indefinitely without showing signs of nitrogen starvation. Singh found the algal film that developed on paddy rice soils in the United Provinces and in Bihar was composed of blue-green algae, all of which were active nitrogen fixers. He found that his species of *Anabaena*, which came from Indian rice-fields, could excrete over 40 per cent of the nitrogen fixed as soluble organic compounds, and although these compounds may not be immediately assimilable by the rice,[3] they are probably rapidly rendered so. Nitrogen-fixing blue-green algae are often the dominant organisms in the algal crusts which form on desert soils, and these crusts may be high in nitrogen.[4] There is no evidence yet that algae play any significant role in enriching the soils of the temperate regions with nitrogen, although species belonging to genera containing nitrogen-fixing forms are fairly widespread.

Green algae have not yet been shown to fix nitrogen, though this may only be because no systematic search for nitrogen-fixing green algae has been made using modern techniques. A symbiosis has often been postulated between them and *Azotobacter*, the algae supplying the bacteria with carbohydrates and the bacteria fixing nitrogen. Several workers claim to have found nitrogen-fixing bacteria on the mucous sheaths of algae, though the algae appear all to belong to the blue-green and not the green algae, though not necessarily to the Nostococcaceae.[5] J. L. Stokes,[6] using two strains of *Azotobacter* and nine species of green algae, failed to find any nitrogen fixation by the bacteria, or, indeed,

[1] K. Drewes, *Zbl. Bakt.* II, 1928, **76**, 88; F. E. Allison, S. R. Hoover and H. J. Morris, *Bot. Gaz.*, 1937, **98**, 433; P. K. De, *Proc. Roy. Soc.*, 1939, **127** B, 121; G. E. Fogg, *J. Expt. Biol.*, 1942, **19**, 78; R. N. Singh, *Indian J. Agric. Sci.*, 1942, **12**, 743.

[2] H. Bortels, *Arch. Mikrobiol.*, 1940, **11**, 155.

[3] Engle and McMurtrey found that tobacco plants in water culture could not use any nitrogen that may have been excreted by a nitrogen-fixing strain of *Nostoc* growing in the solution.

[4] J. E. Fletcher and W. P. Martin, *Ecology*, 1948, **29**, 95.

[5] H. Fischer, *Zbl. Bakt.* II, 1904, **12**, 267 (*Oscillatoria*); J. Jones, *Ann. Bot.*, 1930, **44**, 721 (*Nostoc*, *Rivularia* and *Glœocapsa*).

[6] *Soil Sci.*, 1940, **49**, 265.

any stimulation of their growth, although about 10 per cent of the carbon assimilated by the algae was excreted, but this experiment can obviously not be taken as evidence that there is no symbiosis between *Azotobacter* and non-nitrogen-fixing strains of the blue-green algae.

One can summarise our present-day knowledge of the importance of algae in the economy of the soil by saying that they have been shown to be of great importance in colonising bare soil or soil devoid of organic matter, but that only the blue-green algae have proved important agriculturally, and then only in hot climates. It is possible that they are of prime importance in the cultivation of rice, which is grown under water-logged conditions, by supplying the rice roots with free oxygen and by fixing atmospheric nitrogen which they can use either directly or indirectly; and, since rice forms the staple diet of nearly half the human race, this role is, on a world agricultural basis, by no means negligible.

Protozoa

E. J. Russell and H. B. Hutchinson[1] were the first to suggest that protozoa played an active part in the microbial life of the soil, for they assumed that their activity could explain some of the consequences of partially sterilising a soil. Since then protozoa have been found in soils all over the world, and H. Sandon[2] has given detailed lists and descriptions of the various species known up to 1927.

Protozoa are minute animals, and the soil forms consist mainly of rhizopods and flagellates, though a few ciliates can usually be found. The rhizopods include the amoebae, of which *Naegleria gruberi* and *Hartmanella hyalina* are typical representatives, and the testaceous rhizopods, which are similar organisms, but which have a hard shell covering parts of their body, of which *Difflugia* and *Euglypha* are common soil genera. The soil amoebae vary enormously in size, the common small ones, such as are shown in Plate VII, being from 10 to 40 μ, but they go up to giant forms several tenths of a millimetre in size. The flagellates have one or more flagellae to help them move, and are usually small organisms 5 to 20 μ in length. The commonest soil forms are species of *Cercomonas*, *Oicomonas* and *Heteromita*. The ciliates, which have many short cilia covering the whole or part of their bodies, are most commonly represented by *Colpoda cucullus* and *C. steinii*, and are usually 20 to 80 μ in length.

The soil protozoa are typically small organisms, considerably smaller than the normal protozoal fauna of stagnant water for example, but whereas the water forms have a large volume of space in which they

[1] *J. Agric. Sci.*, 1909, **3**, 111; 1913, **5**, 152.
[2] *The Composition and Distribution of the Protozoan Fauna of the Soil*, Edinburgh, 1927.

can move, the soil forms are restricted to moving in the soil pores, and then only in those containing some water, for they cannot move in dry soil. Furthermore, they can only be active when living in a water film. The majority form cysts during their life-cycle, and in this state they can withstand desiccation, though whether desiccation itself can encourage encystment has not been definitely established. Others can apparently go into a state of suspended animation when the soil dries out, reviving immediately it becomes damp again.[1] Encystment is a definite phase in the life-cycle of some soil amoebae, so that the number of active amoebae of these species present in the soil depends on the rate of encystment and of hatching. Further, the rate of hatching seems to be dependent on the type of bacteria growing in the neighbourhood of the cysts, presumably because hatching is stimulated by products of excretion specific to these groups of bacteria.[2]

Protozoa, or protozoa-like organisms, can feed in three ways: some possess chlorophyll and are autotrophic, but these are confined to a few genera of flagellates such as *Euglena*; some, again mainly flagellates, can feed saprophytically, absorbing nutrients from solution in pure cultures, but what proportion of these do this in the highly competitive environment of the soil is not known; most can feed, and normally only feed, by capturing and digesting solid particles such as bacteria.

Bacteria form the staple food supply of the protozoal population, though small algae, yeasts, flagellates and amoebae are also ingested. But not all bacteria can serve as food. Amoebae, for example, will eat some species of bacteria voraciously, other species only if there is no more acceptable source of bacteria available, and other species not at all.[3] Singh has found that these inedible species include practically all the bacteria producing red, green, blue or fluorescent pigments so far tested, and some of these seem to excrete substances that are definitely toxic to the amoebae. Thus, the protozoa must exert a strong selective influence on the composition of the bacterial population.

The effect of protozoa used to be considered entirely harmful to bacterial life, it being thought that the protozoa reduced the beneficent action of the bacteria in maintaining soil fertility, but it has now been established that some bacteria, in pure culture, work more efficiently in the presence than in the absence of predaceous protozoa. For example, D. W. Cutler and D. V. Bal[4] showed that *Azotobacter* fixed more nitrogen when mixed with the ciliate *Colpidium colpoda*, and Table 34, taken from D. W. Cutler and L. M. Crump's[5] book, shows

[1] J. M. Watson, *Nature*, 1943, **152**, 694.

[2] I am indebted to Miss L. M. Crump for these unpublished observations of hers.

[3] P. Frosch, *Zbl. Bakt.* I, 1897, **21**, 926; R. Oehler, *Arch. Protistenk.*, 1916, **37**, 175; L. B. Severtzova, *Zbl. Bakt.* II, 1928, **73**, 162; B. N. Singh, *Ann. Appl. Biol.*, 1941, **28**, 52, 65; 1942, **29**, 18; *Brit. J. Expt. Path.*, 1945, **26**, 316.

[4] *Ann. Appl. Biol.*, 1926, **18**, 516.

[5] *Problems in Soil Microbiology*, London, 1935.

the influence of amoebae on the rate of oxidation of sugars by bacteria. The bacterial efficiency is here defined as the weight of carbon dioxide produced in millionths of a gramme by 1,000 million bacteria per twenty-four hours, when the bacteria and amoebae are growing in an aerated solution.

TABLE 34

Average Efficiencies per 1,000 million Bacteria at Different Bacterial Densities in the Presence and Absence of Amoebae (Cutler and Crump)

Density of bacteria in millions per cubic centimetre of solution	Weight of CO_2 produced in 10^{-6} gm. per 1,000 million bacteria in 24 hours	
	Bacteria + amoebae	Bacteria alone
0–100	73·2	—
100–200	15·6	9·3
200–300	13·4	7·9
300–400	10·6	8·3
400–500	10·1	3·7
500–600	6·2	3·5

Protozoa cannot yet be counted directly in the soil. The older methods for determining their numbers were based on letting them feed on an uncontrolled bacterial population, but B. N. Singh[1] has recently devised a more reliable method in which they are counted on a controlled population of an edible species of bacteria. The numbers of protozoa present in the soil, as determined by the older methods, vary rapidly from day to day, both in the total number of a species present and in the proportion of the species in an active form. Thus, the numbers of a given species can vary from a few hundreds to as many hundred thousands and the proportion encysted from 0 to 100 per cent within twenty-four hours. The cause of these fluctuations is not known, but there is no reason to believe that they are spurious effects introduced by an unsatisfactory counting technique.

There must presumably be a relation between the numbers of protozoa and the numbers of bacteria present in the soil. Both numbers vary from day to day, though it is probable that the protozoal numbers show relatively much greater variations than the bacterial. The older work on these variations is of doubtful validity, since the bacterial numbers were determined by platings which, as has already been mentioned, only count about 1 per cent of the bacteria present in the soil. Thus, D. W. Cutler, L. M. Crump and H. Sandon[2] found that

[1] *Ann. Appl. Biol.*, 1946, **33**, 112. [2] *Phil. Trans.*, 1922, **211** B, 317.

the numbers of active amoebae in a Rothamsted soil varied inversely with the number of bacteria, a result confirmed by C. B. Taylor[1] if the bacteria were counted by the plating technique, but not if the total cell count method was used. It is, in fact, unlikely that there is any close connection between total active amoebal and bacterial numbers, for the amoebae have strong preferences for certain bacterial species and great intolerance for others.

These large short-period fluctuations in protozoal numbers make it difficult to study the effects of external conditions on the protozoal fauna, as only factors having a very large effect on numbers are sufficient to override them. The effect of season can, however, be demonstrated, for at Rothamsted protozoal numbers are higher in spring and autumn than in summer or winter. On the other hand, protozoal numbers do not seem to be very sensitive to changes in the moisture content, aeration or *p*H of the soil, nor even to the organic matter content of the soil, although the bacterial numbers are. Thus, on the permanent mangold field (Barnfield) at Rothamsted, B. N. Singh found that a plot which had received no manure for nearly ninety years contained between 500 and 11,000 active amoebae on nine different sampling dates from April 1945 to August 1946; a plot which had received many annual dressings of 14 tons of farmyard manure contained between 6,000 and 45,000 on these same sampling dates; and a plot that had received for many years a heavy dressing of fertiliser without any farmyard manure contained between 9,000 and 31,000. The organic carbon in the two soils receiving no farmyard manure was about 0·8 per cent, whilst in the farmyard manure plot it was about 2·5 per cent, and the bacterial numbers, which were determined by total cell count on only two of these occasions, were between 5,000 and 8,000 million on the farmyard manure and between 2,000 and 3,000 million on the other two. A similar example from Broadbalk Field at Rothamsted is given in Table 42 on p. 194.

A rough estimate can be made of the number of bacteria consumed by the soil protozoa, for Cutler and Crump found that the typical soil amoebae, *Naegleria gruberi*, in pure culture needs about 130,000 bacteria between fissions,[2] so that if its numbers increase from 26,000 to 416,000 per gm. of soil in twenty-four hours—a not uncommon increase to occur in the soil—it would have to consume 52,000 million bacteria, if its efficiency was the same in the soil as in the culture. Thus this species alone would have to consume the total bacterial population, as estimated by the direct method, about ten to fifteen times a day for this increase in its numbers to be possible. As there are many other protozoa and organisms predaceous on the bacteria in the soil at the same

[1] *Proc. Roy. Soc.*, 1936, **119** B, 269. [2] *Problems of Soil Microbiology*, London, 1935.

time, the bacterial population must have a high rate of reproduction to supply enough food to maintain the numbers of the predators.

Amoeboid and Flagellate Stages of Other Organisms

A number of organisms which look like flagellates and amoebae may not be protozoa at all, but a stage in the life-cycle of organisms belonging to other groups. Using modern techniques, K. B. Raper has described in some detail certain species of Acrasieae,[1] which have an amoeboid stage termed Myxamoebae. During this stage these organisms live in the soil as amoebae feeding on bacteria, and reproduce by simple fission, but at some stage in their life-history they congregate together, forming characteristic structures that produce spores, which grow into amoebae when conditions for growth become favourable again. B. N. Singh[2] has shown that British soils only contain two species of these organisms, both belonging to the genus *Dictyostelium*, and he isolated these two from thirty-three out of the thirty-eight arable soils, but only from three out of the twenty-nine pasture soils he examined.

In the same way organisms which are flagellates during part of their life-cycle may belong to the algae or fungi. In particular, there are species of soil myxomycetes, or slime fungi, that exist as flagellates during part of their life-cycle, feed on bacteria and divide by simple fission; but at another stage pairs of flagellates will fuse and grow into a large multinucleate plasmodium, or mass of naked protoplasm, behaving as a large amoeba and continuing to feed on bacteria, yeast, fungal mycelium and small protozoa. Under certain conditions, not yet known, it breaks up into spores which in due course become flagellates again.

There are also large, amoeboid-like organisms in the soil that feed on bacteria and small protozoa and are multinucleate like myxomycete plasmodia, but that do not appear to give rise to flagellates. T. Goodey[3] isolated two species of such multinucleate organisms, which he put in the genus *Leptomyxa*, and B. N. Singh[4] has recently shown that one of these species is widespread in British soils. He isolated it from all the arable soils he examined, where it numbered about 1,000 per gram of soil, but he only found it present in about one-third of the pasture soils.

[1] See, for example, *Amer. J. Bot.*, 1940, **27**, 436, for pictures of these organisms.
[2] *J. Gen. Microbiol.*, 1947, **1**, 11, 361.
[3] *Arch. Protistenk.*, 1914, **35**, 80.
[4] *J. Gen. Microbiol.*, 1948, **2**, 8, 89.

CHAPTER XI

THE SOIL FAUNA OTHER THAN PROTOZOA

THE INVERTEBRATE FAUNA of the soil has not been systematically studied in any detail. Several workers have, however, given lists of genera found in one or two localities, but quantitative work on the numbers of different organisms present and how they live in the soil has been greatly hampered by lack of suitable techniques. Reliable methods capable of separating out the larger members of the fauna from the soil itself are only slowly being devised, and they are probably still lacking for the smaller members, so that censuses are only available for parts of this population, and until detailed censuses are available, the importance of the different genera of the soil fauna in the general life of the soil cannot be estimated. A beginning has also recently been made in the study of the food of some members of this population, both by the aid of a direct microscopic examination of the soil and also by an examination of the gut contents of some of the species present; but it remains true to say that the present-day knowledge of the ecology of this population is incomplete and one-sided.

The size of the soil invertebrate population depends both on the food supply and also on the physical condition of the soil. The soil invertebrates need fairly well-aerated soil for active growth: they cannot thrive in water-logged soils nor in wet soils that have been puddled by the trampling of cattle. They therefore tend to concentrate in the top 1–2 inches of the soil surface, and in many soils only a few groups, such as the earthworms, are common in the next 2–3 inches. The food supply determines the size of the population in normal soils, and it consists either of living or dead plant tissues or of the soil microflora. The primary animal population feeding on this fundamental source of supply supports two other populations, one feeding on the excreta or faeces of the primary population and the other feeding on the population itself. Animals feeding on dead plant tissues or their associated microflora are commonly called saprophagous, on living plants phytophagous, on animal excreta coprophagous, and on other animals predaceous. The higher and the larger members of the community may use all these methods of obtaining their food, though, generally speaking, only specialised genera are predaceous on the larger invertebrates.

Some foresters have begun to study the food supply of this animal population and are coming to believe that any one bit of primary

organic matter passes through the gut of a large number of animals before it is degraded into resistant humus. A. P. Jacot,[1] for example, thought that the process of decomposition of material such as plant roots is as follows: first, the more resistant material is softened by fungi, then it is eaten by saprophagous animals, particularly mites, which continue the decomposition of the plant material, possibly with the aid of a microbial population in their gut; and finally the undigested material is excreted and forms the food supply for a whole chain of other animals until it is converted to resistant humus-like material. In fact, if soils poor in earthworms are examined under the microscope[2] a great part of the "humus" present is recognisable as the excreta of soil invertebrates. It is also possible that animals are important producers of humus in cool well-aerated dung-heaps, for they can occur in very large numbers under these conditions[3] and must be responsible for an appreciable fraction of the decomposition taking place.

The digestion of this organic matter naturally involves the gradual oxidation of its carbon into carbon dioxide and its nitrogen into simpler forms, thus resulting in a decreasing carbon-nitrogen ratio. Thus, L. Meyer[4] found that earthworms feeding on rye-straw composted with basalt meal reduced its C/N ratio from 23 to 11 during a period of two years whilst the soil micro-organisms alone only reduced it to about 18 during the same period. Very little is yet known about the types of material in the plant debris that are available to the different species of the saprophagous fauna. But it appears probable,[5] for example, that some woodlice and millepedes can only digest the sugars, starches and accessible proteins in the plant tissues; some termites and snails can digest part of the celluloses and hemicelluloses contained in the plant tissues, and some nematodes and mites can live symbiotically with, or predaceously on, the cellulose-decomposing bacteria attacking the tissues. It is also possible in many forest and pasture soils that fungal mycelium forms the transition compounds between plant and animal tissue, for the majority of the soil fauna appear to have no power of digesting the celluloses, hemicelluloses or lignins in the dead plant tissues, but this is attacked by fungi and converted into their protoplasm, and it is their mycelia that forms the principal food supply of a large proportion of the mites and springtails (*Collembola*), as is shown by a study of the contents of their gut.[6]

The soil fauna can for many purposes be divided into two groups:

[1] *Ecology*, 1936, **17**, 359.
[2] W. Kubiena, *Bodenk. PflErnähr.*, 1942, **29**, 108. See also P. E. Müller, *Studien über die natürlichen Humusformen*, Berlin, 1887.
[3] H. Franz, *Bodenk. PflErnähr.*, 1943, **32**, 336.
[4] *Bodenk. PflErnähr.*, 1942, **29**, 119.
[5] H. Franz, *ForschDienst.*, 1942, **13**, 320.
[6] K. H. Forsslund, *Medd. Skogsförsöksanst.*, 1945, **34** 1.

the microfauna, which are too small, when mature, to affect the pore size in the soil, and so are without mechanical influence on it, and the macrofauna, which increase the size of the pores in which they move. The former group includes the protozoa, rotifers and nematodes, which live in the soil water films, and the micro-arthropods—the mites and springtails—which live in the air spaces.

The larger soil fauna have three very important effects in the soil: they assist the aeration and drainage of the soil through the channels and burrows they leave behind them as they move through the soil in search of food; they macerate and grind up the plant litter they eat, excreting it in a form more readily available to the attack of the soil micro-organisms; and they distribute this macerated plant debris together with some of the microflora throughout the volume of soil in which they are working. The saprophytic soil fauna can have two other effects on the soil. In the first place, their gut often forms a suitable environment for the conversion of plant residues into mull humus. This is particularly true for animals like earthworms and some millepedes that ingest soil along with their food, but it is also true of many other animals that only ingest organic matter. Unfortunately the chemistry of the changes taking place in the gut of the various species of the soil fauna has not been investigated. In the second place, many of the larger saprophytic animals attack freshly dead plant tissues, and if for any reason the supply of suitable food is reduced, they will start attacking the corresponding plant tissue before it is dead, thus sometimes becoming a serious pest to farmers and gardeners. This typically happens on the farm when the rate of supply of organic matter to the soil is suddenly reduced, as, for example, when a long ley or an old pasture is ploughed out.

The effect of the soil fauna in moving soil is sometimes very considerable. Moles, ants and termites may all put appreciable amounts of subsurface or subsoil on the soil surface, and in the semi-arid steppes there are a number of other mammals that burrow into the soil, down to 10 feet at times, bringing up soil from this depth and leaving it as mounds on the surface. These burrows often get filled with surface soil giving the typical channels of black soil, or *crotovinas* to use the Russian word, in the light coloured parent material in these areas, as is illustrated in Plate XXX. On poorly-drained soils other burrowing animals, such as crayfish, can be active. Thus J. Thorp[1] has described how these animals will make burrows down from the surface to the water table, if it is within the top 10 feet; and he found them active on many soils having a pronounced clay pan. Thus these animals are not only

[1] *Sci. Mon.*, 1949, **68**, 180. He gives field descriptions of the soil-moving effects of many of these animals with estimates of the weight of soil they move.

bringing subsoil up to the surface but also burrowing through a clay pan and so assisting in the mass movement of water.

The soil fauna can be of indirect importance in agriculture through some of them being alternative hosts to certain animal parasites, and this particularly concerns the fauna of pastures, for the grazing animal can easily pick up infected soil invertebrates with its fodder. Thus, the liver fluke and some of the lungworms of sheep must pass a part of their life-cycle in certain gasteropods (slugs and snails); so that good drainage of pastures, by reducing the gasteropod population, reduces the incidence of these diseases. Again, some sheep and horse tapeworms have, as alternative hosts, species of orebatid mites which are common in old matted pasture but which do not flourish in young leys. But it is not always possible or desirable to control the alternative host; thus some lungworms of pigs have certain common species of earthworms as alternative hosts, and it is both difficult, and probably also undesirable, to try to reduce the incidence of this disease by eliminating the earthworm host.

The invertebrates that have been most frequently recognised in soils include nematodes, earthworms and perhaps potworms, acarine mites, millepedes and centipedes, a few crustacea and gasteropods, and many genera of insects, photographs of some of which are reproduced in Plates VIII and IX; but the warning must be repeated that the techniques used have never really been adequate to make a complete census of the population, so that there may be groups of small animals, such as flatworms (*Planarians*), rotifers, nematodes and the smaller mites which have either been missed or else greatly under-estimated. As an illustration of this trouble the age distribution of the population of a given animal in the soil has often been wrongly determined, because the techniques used have commonly separated out a much larger proportion of the older, and larger, individuals than of the younger and smaller. It is probable that immaturity is the outstanding characteristic of the soil animals, as is shown in Table 35, for the size distribution of wireworms.

Over half the population is seen to be in the smallest group, a group which previous techniques had almost missed.

Only a few analyses of the soil invertebrate population have been made[1] and, with the exception of Bornebusch's detailed monograph and a short section in Morris's first paper, the published data only give the

[1] H. M. Morris, *Ann. Appl. Biol.*, 1922, **9**, 282, and 1927, **14**, 442, for Rothamsted fields; M. Thompson, ibid., 1924, **11**, 349, and E. E. Edwards, ibid., 1929, **16**, 299, for some fields around Aberystwyth; J. Ford, *J. Animal Ecol.*, 1935, **4**, 195, for an Oxford meadow. For forest soils, see C. H. Bornebusch, *Forstl. Forsoegsv. Danmark*, 1930, **11**, 1; A. P. Jacot, *Ecology*, 1936, **17**, 359; T. H. Eaton and R. F. Chandler, *Cornell Agric. Exp. Sta., Mem.* 247, 1942. For tropical soils, see A. H. Strickland, *Trop. Agric. Trin.*, 1944, **21**, 107; *J. Animal Ecol.*, 1945, **14**, 1; 1947, **16**, 1.

TABLE 35

The Size Distribution of Wireworms (Agriotes spp.) in two Cambridge Pastures[1]

Length of wireworm in millimetres	Per cent by numbers in the size class	
	Field 1	Field 2
2–6	59	52
6·1–10	26	23
10·1–14	9	12
14·1–24	6	13

TABLE 36

Numbers of Small Animals found in Soil at Rothamsted[2]

Numbers are in millions per acre in the top 9 in. of soil

	Broadbalk (continuous wheat)		Grassland
	Manured	Unmanured	
Insects:			
Springtails (Collembola)	40·6	28·3	54·1
Beetle larvae (Coleoptera)	5·9	0·9	2·3
Fly larvae (Diptera)	19·4	3·8	11·1
All others	3·4	0·5	11·0
Myriapods	4·5	1·8	1·8
Arachnids:			
Mites (Acarina)	6·5	1·9	2·9
Spiders (Araneae)	0·17	0·07	1·2
Woodlice (Isopods)	0·04	0·05	—
Slugs and Snails (Gasteropods)	0·04	—	0·05
Oligochaetes	2·6	0·6	8·4
Nematodes	1·5	0·2	7·6
Total	84·6	38·2	100·5
Period of observation	Feb. 1936 to Jan. 1937		Apr. 1936 to March 1937

[1] G. Salt and F. S. J. Hollick, *Ann. Appl. Biol.*, 1944, **31**, 52.
[2] K. D. Baweja using W. R. S. Ladell's apparatus.

numbers of animals found without any reference to their weight. Table 36 gives an example of the average number of different groups found during one year in an old pasture field and in two neighbouring plots on Broadbalk Field at Rothamsted, one of which has received 14 tons of farmyard manure almost every year since 1843 and the other none at all during this period.

TABLE 37

Approximate Nitrogen Content and Dry Weight in Pounds per Acre of the Small Animals on Broadbalk Field

	Manured			Unmanured		
	No. in thousands per acre	Nitrogen lb. per acre	Dry weight[1] lb. per acre	No. in thousands per acre	Nitrogen lb. per acre	Dry weight[1] lb. per acre
Earthworms	1010	10	110	460	5	50
Myriapods	1780	4	80	880	2	40
Insects:						
Collembola	2390	0·02	0·2	690	0·005	0·05
Wireworms (*Elateridae larvae*)	200	0·5	4	165	0·4	4
Ants	2950	0·7	6	690	0·2	1
All others	2370	0·3	3	930	0·1	1
Arachnids[2]	970	0·2	2	347	0·05	0·5
Potworms and Nematodes	3600	0·2	3	790	0·05	0·8
Total about		16	210		7–8	100

The effect of farmyard manure in the arable field and of organic matter in the pasture is to put up the populations considerably. But these figures refer only to the numbers present, and since some of the animals are almost microscopic and others large, the table gives no indication of the relative importance of these groups in the soil. One can make a rough calculation of the dry weights of the animals on the two Broadbalk plots using some older and less complete data of Morris,[3] which are given in Table 37. This shows that the really numerous animals are so small as to make a negligible contribution to the total dry weight, but that the earthworms and myriapods form nearly 90 per cent by dry weight of the population, and this result would not

[1] Morris does not give these dry weights; they have been calculated from the nitrogen contents of the different groups and their contribution to the nitrogen per acre.

[2] The figures for nitrogen and dry weight were not determined. Morris assumed the arachnids had the same nitrogen content as an equal number of insects.

[3] *Ann. Appl. Biol.*, 1922, **9**, 282.

be very different if the smallest animals had been greatly underestimated in numbers, as they make such a small contribution to the total weight of the soil fauna. Some forest and grassland soils differ from Rothamsted in having more mites than springtails; in fact, mites can account for upwards of 60 to 80 per cent of the total number of animals, and in forest soils may number 40 million or more per acre in the H-layer; that is, the layer below the rotting leaves.[1]

Bornebusch[2] discussed the problem of measuring the importance of the different types of animal in the soil, and concluded that the total weights of each animal do not accurately correspond to the quantity of organic matter oxidised by the animals, for he showed that the small soil animals need considerably more oxygen for respiration, which is equivalent to needing that much more food, per unit of body weight, than do the larger animals. He separated out several groups of animals from the surface layers of ten different Danish forest soils, and determined the live weight and oxygen need for each group. Table 38 gives a summary of his results for two typical soils under beech forest, the first a good mull carrying a flourishing ground vegetation, and the other a raw humus or mor almost bare of ground vegetation.

Mites and springtails abound in these soils and, on the basis of numbers alone, form almost the whole population, though they make a negligible contribution to its total weight. But their contribution to the total oxygen demand, or to the total quantity of organic matter oxidised away by the population may become appreciable, particularly in the raw humus or mor soils. But the table illustrates the important point that the oxygen demand of the soil fauna, or the rate at which it oxidises the soil organic matter, does not necessarily increase with increases in the total number of animals present.

These results also show, as did Morris's (see Table 37), that where earthworms thrive they form the major portion of the total weight of the animal population. Thus Bornebusch found that the weight of all animals excluding earthworms varied from 35 to 170 lb. per acre for the ten different soils he studied, but in the two good mull soils of his group the half a million earthworms present weighed about 500 lb. per acre. Further, in two forest sites, on which he only took a few samples, the 1–1½ million per acre weighed 1,500–1,800 lb., which, as he points out, equals the weight of livestock carried per acre on first-class Danish pastures. The relation between the numbers of earthworms and their weight is not, however, simple for it depends on the species present. Thus, in Table 38 the average weight of an earthworm in the mull is about 300 mgm.—they were mainly the medium-sized

[1] T. H. Eaton and R. F. Chandler, *Cornell Agric. Expt. Sta., Mem.* 247, 1942.
[2] *Forstl. Forsoegsv. Danmark*, 1930, **11**, 1.

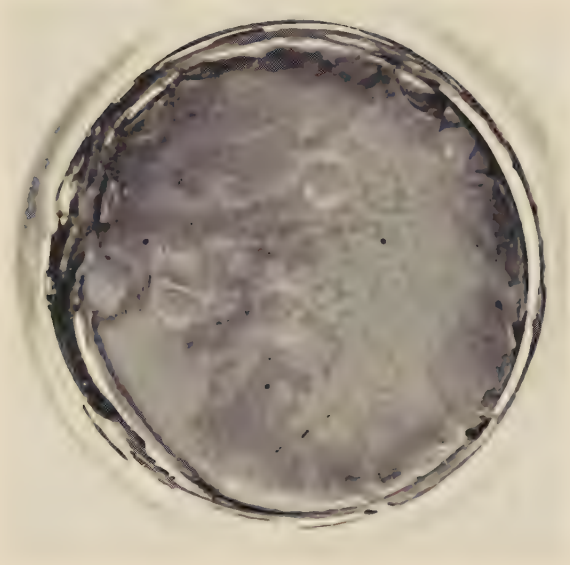
Allolobophora turgida, now known as *A. caliginosa*—whilst on the raw humus soil they are mainly the small *Dendrobaena octoedra*, which only weigh about 67 mgm.

TABLE 38

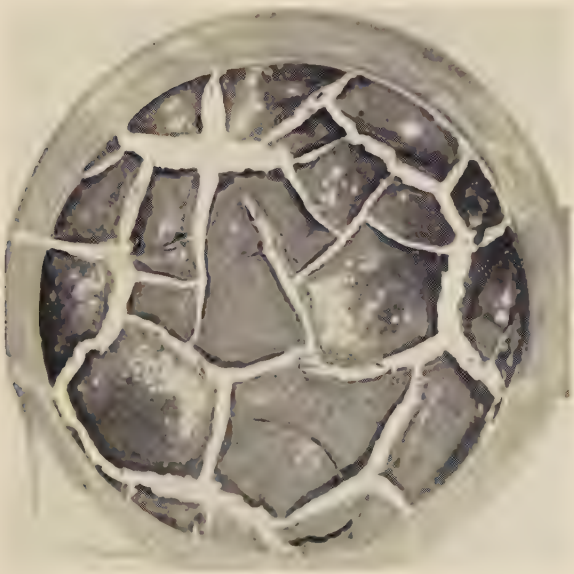
The Numbers, Weights and Oxygen Consumption of Various Groups of Animals in Danish Forest Soils

	Mull soil under beech pH 6·1–5·8			Raw humus under beech pH 5·6–3·6		
	Numbers in millions per acre	Per cent contribution to the total weight of the animals present	Per cent contribution to the total oxygen consumption of the animals present	Numbers in millions per acre	Per cent contribution to the total weight of the animals present	Per cent contribution to the total oxygen consumption of the animals present
Earthworms	0·72	75·1	56·2	0·33	22·4	12·2
Potworms	2·16	1·5	6·0	3·16	6·5	14·4
Gasteropods	0·42	7·0	7·3	0·21	13·4	7·5
Millepedes	0·72	10·6	15·0	0·16	4·7	3·9
Centipedes	0·32	1·8	3·5	0·08	2·1	2·0
Mites and springtails	17·85	0·4	4·5	45·5	2·3	16·1
Diptera and Elateridae larvae	0·99	2·4	3·7	5·28	43·8	35·2
Other insects, isopods and spiders	1·91	1·2	3·8	2·63	4·7	8·7
Total number of animals	25·0 million per acre			57·2 million per acre		
Total weight of animals	630 lb. per acre			214 lb. per acre		
Oxygen used per sq. m. at 13° C.	0·33 litre per day			0·20 litre per day		

One other use can be made of the respiration figures given in Table 38. Bornebusch estimated the annual oxygen consumption of the animal population in the various soils he studied; it was about 90 and 60 gm. per sq. m. per year in the two soils given in the table, and this is approximately the weight of food oxidised by the soil animals, for about 1 gm. of oxygen is needed to oxidise 1 gm. of organic matter to carbon dioxide. He further estimated that the annual leaf fall returns about 400 gm. of organic matter per sq. m. to the soil, so that, ignoring the weight of plant roots being decomposed, about which nothing is known, the animal population is responsible for the oxidation of about 15 to 20 per cent of the plant remains.



Dried paste of a deflocculated sodium saturated Lower Lias clay



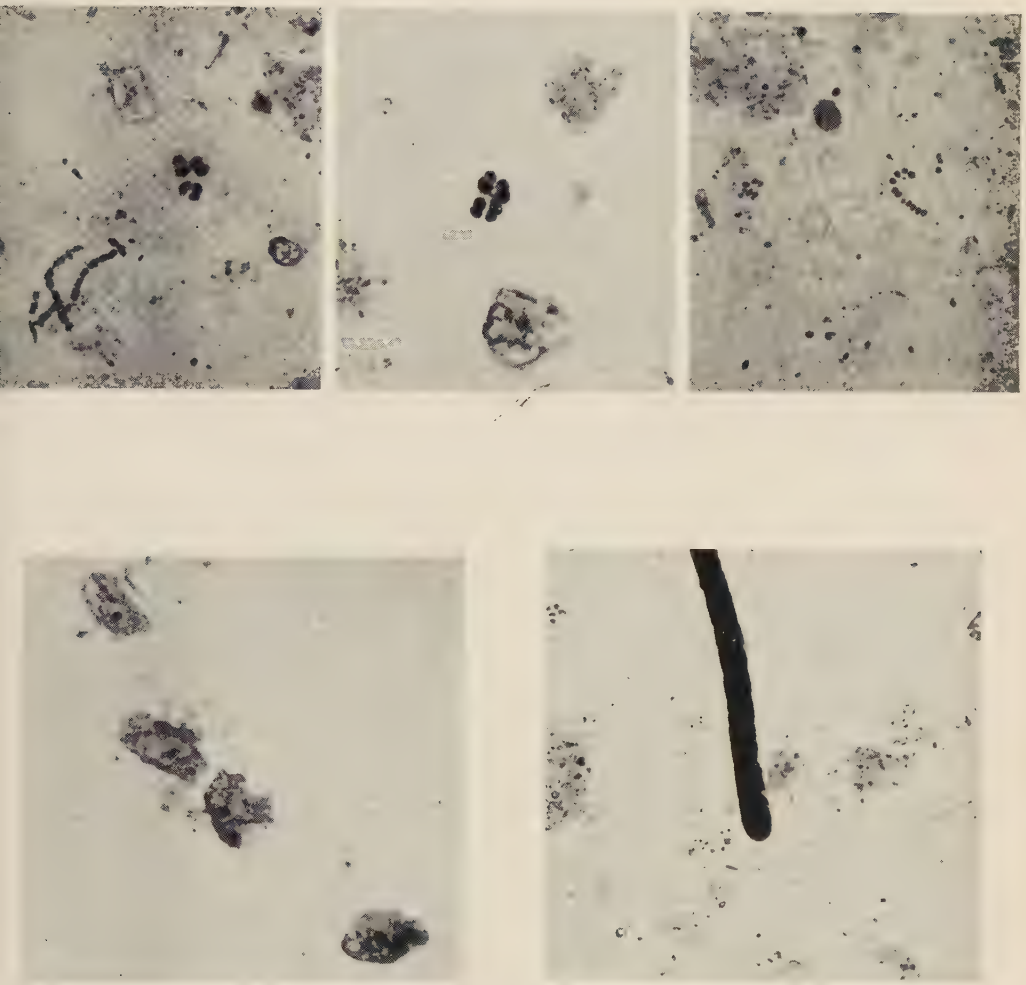
Dried paste of a sodium saturated Lower Lias clay flocculated with sodium chloride

(*p. 132*)

Electron microscope photographs of three types of bacteria (x 25,000)

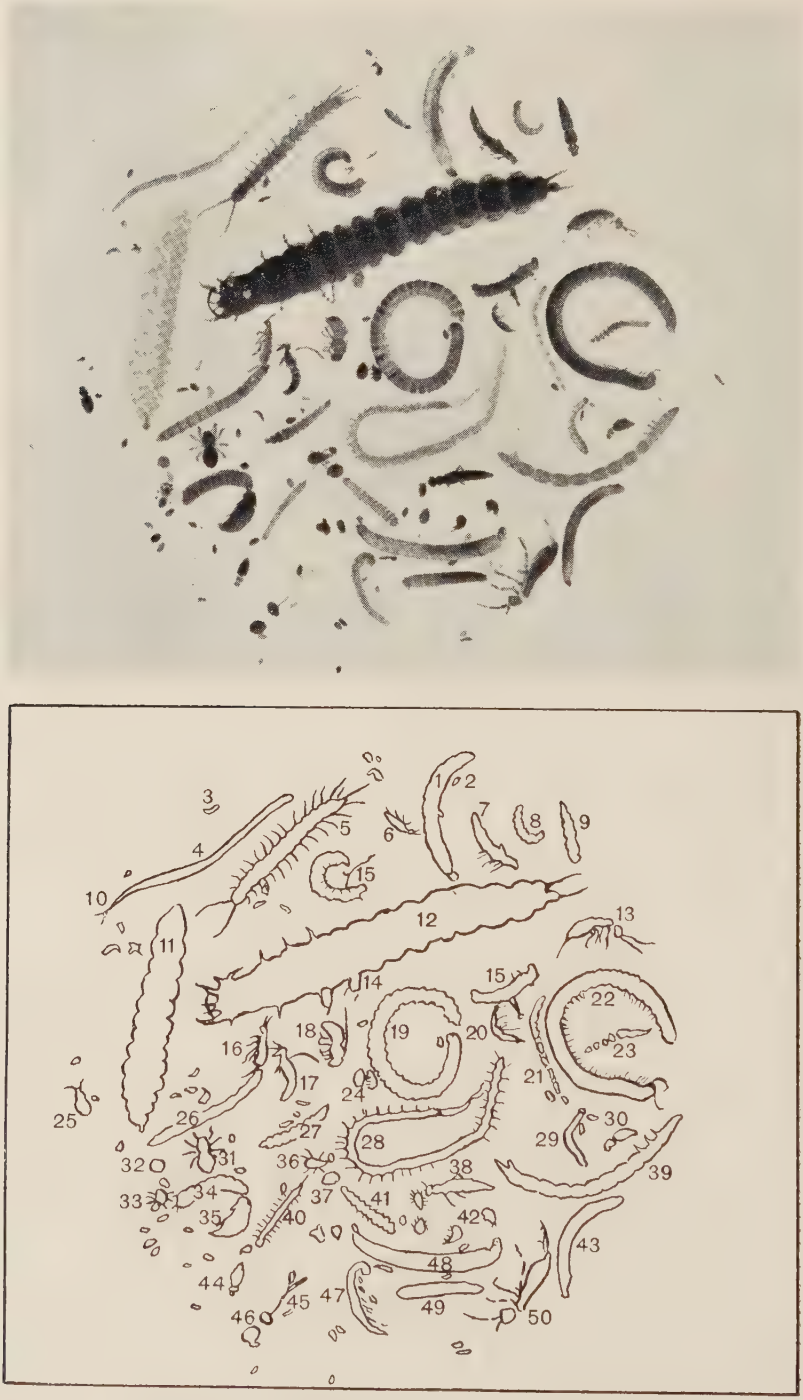
The first two have been gold shadowed before being photographed. The second shows flagellae of the bacteria

(*p. 136*)



Bacterial colonies (*top*) and amoebae and a fungal hypha (*bottom*) in the soil, as displayed by Jones and Mollison's direct staining technique (x 1,000)

(*p. 137*)



Typical members of the soil fauna (natural size)

(*For key, see opposite page*)

(*p. 172*)

Plate IX:

1. Earthworms Lumbricus sp. (Oligochaeta)
2. Beetle larva Carabidae (Coleoptera)
3. Chafer grub Phyllopertha sp. (Coleoptera)
4. Slug Agriolimax sp. (Mollusca)
5. Leatherjacket Tipulidae (Diptera)
6. Millepedes (Diplopoda)
7. Cutworm Agrotidae (Lepidoptera)
8. Centipede (Chilopoda)

Plate VIII:

Chilopoda: Centipedes
4, 5, 28, 40

Diplopoda: Millepedes
19, 22, 41

Arachnida

(*a*) Araneae: Spiders
31, 33

(*b*) Acarina: Mites
2, 14, 36: Gamasidae
24, 32, 37, 45: Oribatidae
42: Tyroglyphidae

Insecta

(*a*) Collembola: Springtails
3, 6, 10, 13, 16, 20, 50

(*b*) Lepidoptera
8: Larva

(*c*) Coleoptera
7, 9, 17, 30, 35, 38, 44: Staphylinoidea (adults)
15, 23, 27, 29, 34, 41: Staphylinoidea (larvae)
25: Carabidae (adult (small species))
12: Carabidae (larva (large species))
21, 26, 39, 45: Elateridae (larvae) Wireworms

(*d*) Diptera
1, 43, 48, 49: Bibionidae (larvae)
11: Cyclorrapha (larva)
18: Anthomyidae (adult)

Plate X

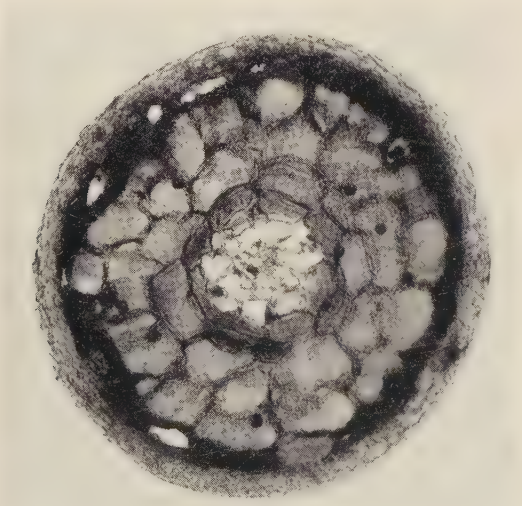
Part of the root system of Scots pine (*Pinus sylvestris*), showing differentiation into long roots and short forked mycorrhizas

Lower photograph: natural size; upper photograph: x6

(*p. 220*)

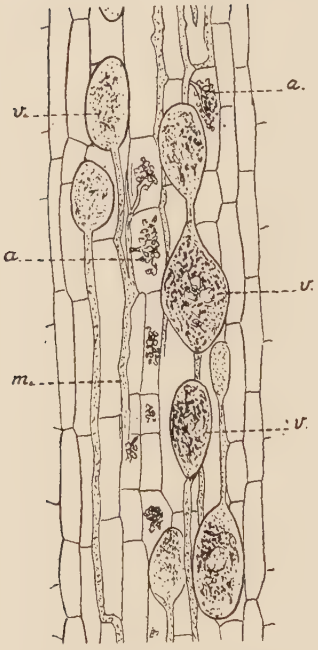
(Half natural size) (x 7)

Part of the root system of the date palm (*Phoenix dactylifera*). The fine feeding roots are all mycorrhizas

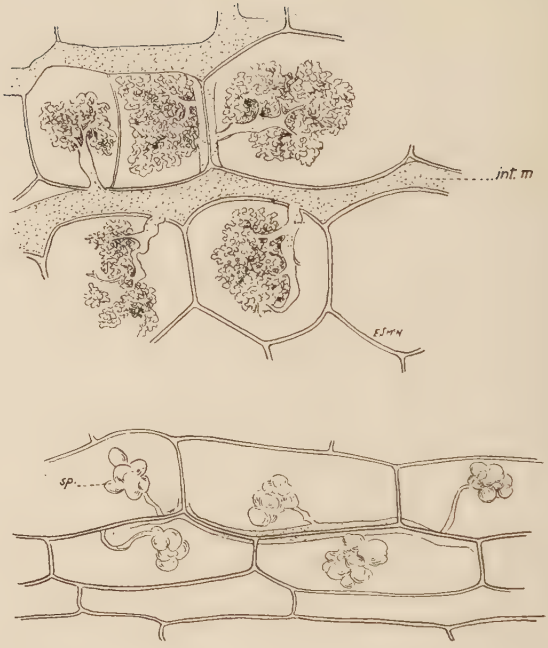


Transverse section of a mycorrhiza of Scots pine, formed by association with *Boletus bovinus* (x 130)

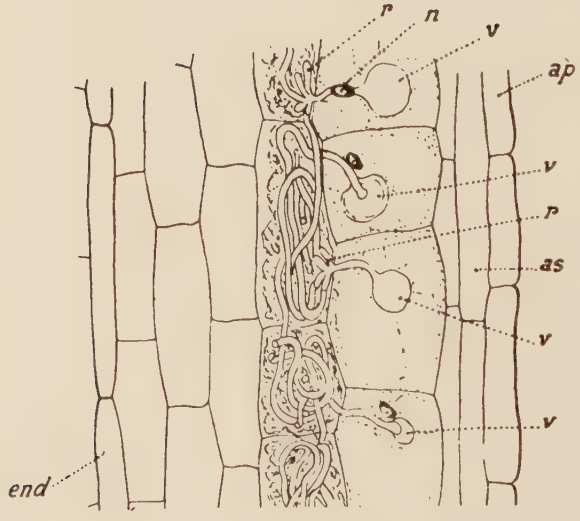
(*p. 220*)



Vesicles in a strawberry rootlet (x 60)



Arbuscules in strawberry rootlets (x 600) (*Top*) well developed; (*Bottom*) partially decomposed



Vesicles and pelotons in autumn crocus roots (x 210)

m = mycelium; int. m. = intercellular mycelium;
v = vesicles; a = arbuscules;
sp = sporangioles;
end = endodermis;
ap = as = epidermis

(p. 226)

Nematodes

The nematodes or eelworms are non-segmented worms with cylindrical or spindle-shaped bodies, and a large proportion are about 0·5 to 1·5 mm. long and about forty to fifty times as long as they are broad. Soil nematodes fall roughly into three groups:

1. Those living on decaying organic matter, as well as on the soil microflora and possibly on the protozoa. They are omnivorous and form the most numerous group both in numbers and species.

2. Those predaceous on the soil fauna, including other nematodes, tardigrades and oligochaetes. Many of these species can use a wide range of foods, but a few, such as some of the larger dorylaims, seem to be restricted to oligochaetes or other specific groups of animals.

3. Those parasitic on plants and usually fairly specific in their food requirements. They have been more extensively studied than the other soil nematodes.

H. Mikoletzky,[1] H. Franz[2] and C. Overgaard Nielsen[3] have studied the composition of the nematode populations in a variety of soils in Bucovina, Austria and Denmark, and recognised nearly 200 different species; but of these only between 20 and 30 were common. The composition of the population was not found to be very dependent on the soil or on the method of soil management used in this part of Europe. Very little, however, is yet known about the principal sources of food of this free-living population or their effect on the decomposition of the soil organic matter; though Overgaard Nielsen, both from an examination of the gut contents of nematodes extracted from the soil, and from feeding experiments, concluded that most of them were predaceous, feeding on bacteria, algae, protozoa and, for the larger ones, other nematodes, though a proportion sucked the juices from roots and possibly fungal hyphae also. He found no evidence that any fed on plant debris. The population is not confined to the surface of the soil, but most of it is found in the top 10 cm.

Franz, Overgaard Nielsen, A. Stöckli[4] and D. Robertson[5] have counted the number of nematodes in soils, and the first two have also classified them into species, and Nielson has also estimated their weight and their oxygen consumption. Both Nielsen and Robertson found that arable soils contain about 1 million per square metre, weighing about 1 gram (9 lb. per acre) whilst Franz, Nielsen and Stöckli found that pastures contained from 2 to 20 million, weighing between 5 and 20 grams per square metre (45–180 lb. per acre). Nielsen and Stöckli also give the numbers in a mor soil under spruce and in a mixed woodland,

[1] *Arch. Naturgesch.*, 1921, **87** A, No. 8.
[2] *Zool. Jahrb.* (Syst), 1942, **75**, 365.
[3] *Natura Jutlandica*, 1949, **2**, 1.
[4] *Ber. Schweiz. Bot. Ges.*, 1943, **53** A, 160.
[5] *Proc. Roy. Phys. Soc. Edinb.*, 1926, **21**, 83.

which are similar to those in an arable field. These total weights are therefore small compared with the 100–600 lb. per acre of the remainder of the soil fauna, with the exception of those in some pastures.

The predaceous nematodes may possibly help to keep the numbers of the plant parasitic nematodes in control, for they can certainly feed on them. Numerous investigators have tried to alter the soil conditions in such a way that these predaceous nematodes would reduce the members of the plant parasites so much that they could not affect the host plant appreciably. So far, however, these attempts have met with little success, possibly because the predaceous nematodes are not specific in their food requirements, but will feed on the saprophytic nematodes and other invertebrates, including young earthworms, as readily as on the parasitic nematodes.

Pathogenic nematodes can be controlled to some extent in hot countries by adding large quantities of organic matter—composts, green manures, molasses and such like—which encourage a very large population of saprophytic organisms, including saprophytic nematodes, to build up. This population in turn allows a larger predaceous population of mites, nematodes and nematode-catching fungi to build up, which are not only predaceous on the saprophytic, but also the plant pathogenic nematodes. Thus the population of pathogenic nematodes can be reduced down to a tenth in a few weeks provided no living roots on which the nematodes are parasitic are present.[1] But this method may be dangerous, as some of the saprophytic nematodes can become parasitic on some species of plants.

Again pathogenic nematodes exist in the soil as cysts, and the active nematodes only hatch out after they have absorbed a sufficient amount of root secretion characteristic of their host plant. This opens up a possible method of control by adding the active compound to the soil when their host plants are absent, so the nematodes hatch out but die of starvation through lack of their host plant. But there is another possible method of control because there are sometimes other plant roots secreting substances which prevent the cysts hatching out when in the presence of the characteristic root secretions of their own host plants. Thus, G. W. Burton *et al.*[2] found strains of Bermuda grass that actively prevented the nematode *Heterodora marioni* attacking the roots of lespedeza provided the two were present in the right proportion.

Earthworms

The importance of earthworms was first stressed by Charles Darwin

[1] M. B. Linford, F. Yap and J. M. Oliveira, *Soil Sci.*, 1938, **45**, 127.
[2] *J. Amer. Soc. Agron.*, 1946, **38**, 651.

in his book *Earthworms and Vegetable Mould*[1]—one of the classics of soil science, and also by V. Henson.[2] But in spite of this early start, and of their obvious importance in soils, very little work has been done on their ecology. Yet both C. H. Bornebusch,[3] working with Danish forest soils, and H. M. Morris,[4] working with Rothamsted arable soils, found that where earthworms flourished they constituted between 50 and 75 per cent of the total weight of the animals present, although on a further calculation of Bornebusch (see p. 176) their effectiveness in decomposing organic matter was not quite as high as this figure might suggest. Further, foresters such as P. E. Müller[5] and W. Kubiena[6] have remarked on the fact that the only obvious animal excreta in soils containing earthworms is that of the earthworm, whilst on soils not containing earthworms the excreta of a large number of other animals becomes obvious. The conclusion seems to be justified, therefore, that where earthworms flourish they dominate the whole soil fauna.

J. Stephenson[7] has described in detail what is known of their zoology. They reproduce sexually; their eggs are laid in cocoons, out of which usually only one young earthworm emerges; they take from six to eighteen months to reach sexual maturity and can live for over six years in captivity, but nothing is known about their average age in the soil. Their separation into genera and species presents great taxonomic difficulties, with the consequence that in the published work on earthworms they have often either not been further classified or, even worse, wrongly classified. The classification of the British species has recently been clarified by the work of L. Cernosvitos and A. C. Evans.[8] Little is known about the frequency of their occurrence, though A. C. Evans and W. J. McL. Guild[9] have shown that four species of *Allolobophora—longa*, *nocturna*, *caliginosa* and *chlorotica*, two of *Lumbricus—terrestris* and *rubellus*, and *Eisenia rosea* are among the commonest in British soils.[10] They vary in size from the large *L. terrestris*, which may have a length exceeding 25 cm. and weighs between 2 and 7 gm., to small species with lengths about 2·5 cm. and weighing about 0·05 gm. At Rothamsted *A. caliginosa*, *A. chlorotica* and *E. rosea* appear to be the principal worms in arable fields, cultivation

[1] Published by J. Murray (London) in 1881, and reissued by Faber & Faber in 1945 under the title *Darwin on Humus and the Earthworm.*

[2] *Ztschr. wiss. Zool.*, 1877, **28**, 354; *Landw. Jahrb.*, 1882, **11**, 661.

[3] *Forstl. Forsoegsv. Danmark*, 1930, **11**, 1.

[4] *Ann. Appl. Biol.*, 1922, **9**, 282; 1927, **14**, 442.

[5] *Studien über die natürlichen Humusformen*, Berlin, 1887.

[6] *Bodenk. PflErnähr.*, 1942, **29**, 108.

[7] *The Oligochaeta*, Oxford, 1930.

[8] *Synopses of the British Fauna*, Linnean Soc., No. 6, 1947.

[9] *Ann. Appl. Biol.*, 1947, **34**, 307.

[10] H. Hopp (*Proc. Soil Sci. Soc. Amer.*, 1948, **12**, 503) found *A. caliginosa* was the dominant species in a Maryland soil with *A. chlorotica* sub-dominant.

operations discouraging the smaller worms less than the larger. The habits of life of the various species differ widely, a fact unfortunately overlooked by some workers. They all appear to obtain part, at least, of their food from the surface of the soil, though some, such as *A. nocturna*, *A. longa* and *L. terrestris*, come on to the surface to collect this food and drag it down into their burrows, whilst the others will pull the food down from underneath the surface. Only *A. nocturna* and *A. longa* of the British species have been shown to make wormcasts on the surface of the soil.[1] *L. terrestris* is a deep burrower and may make a burrow as deep as 5 to 6 feet; *A. nocturna* and *A. longa* make burrows that may be as deep as 12 inches, whilst most of the rest only make shallow burrows. Little is known about the food preferences of different species of earthworms. Earthworms as a whole eat dung, such as cow dung, readily, and in forests eat elm, ash and birch litter more freely than oak and beech, and do not eat pine or spruce litter at all.[2]

Earthworms can only thrive in soils under certain specific conditions. They are intolerant of drought and frost;[3] and hence dry sandy soils, and thin soils overlying rock[4] are not usually favourable environments for them. They need a reasonably aerated soil, hence heavy clays or undrained soils are also unfavourable. Thus under given conditions of management they will be most numerous in loams and less numerous in sands, gravels and clays.[5] They are much more active in spring and autumn, when the surface soil is moist and warm, than in summer when the surface is usually dry, and in winter when it is too cold. A. Stöckli[6] has given an example of the effect of spring rainfall on the weight of earthworm casts produced on a Swiss pasture: 3 tons per acre for the three months April to June one year when the rainfall during this period was 10½ inches, and 10 tons the next when it was 16½ inches.

Earthworms can only flourish in soils well provided with organic matter, such as forest, pasture and heavily manured arable soils. Bornebusch, in Denmark, and T. H. Eaton and R. F. Chandler,[7] in New York State, found between a half and one million earthworms of various species per acre in suitable forest soils; and E. E. Edwards[8] found up to three million per acre in some Welsh pastures. H. M. Morris[9] found about a million per acre on the wheat plot of Rothamsted

[1] A. C. Evans, *Ann. Appl. Biol.*, 1948, **35**, 1.
[2] B. Lindquist, *Svensk. Skogsv. Tidskr.*, 1941, **39**, 179.
[3] For examples of the effect of frost limiting earthworm numbers, see H. Hopp, *Proc. Soil Sci. Soc. Amer.*, 1948, **12**, 503, 508.
[4] W. Kubiena, *Bodenk. PflErnähr.*, 1942, **29**, 108.
[5] W. J. McL. Guild, *Ann. Appl. Biol.*, 1948, **35**, 181.
[6] *Landw. Jahrb. Schweiz.*, 1928, **42**, 1.
[7] *Cornell Agric. Expt. Sta., Mem.* 247, 1942.
[8] *Ann. Appl. Biol.*, 1929, **16**, 299.
[9] *Ann. Appl. Biol.*, 1922, **9**, 282; 1927, **14**, 442.

that has been dunged for over fifty years, and from a few thousand up to half a million on those that had not received any farmyard manure during this period.

A. C. Evans confirmed these findings and found that the actual weight of worms per acre on the undunged plots was proportionately lower than their numbers. Thus, he found the plot receiving farmyard manure had about one million earthworms per acre which weighed about 440 lb., whilst the plots receiving no farmyard manure had from 200,000 to 500,000 weighing between 50 and 100 lb. The numbers and weights in these plots did not seem to be correlated with the fertiliser treatment or the yield of wheat, but much of this variation may have been due to sampling difficulties.

Most earthworms, including all the larger species, need a continuous supply of calcium, which they convert into calcium carbonate and excrete from special glands in their digestive tract. Earthworms are, therefore, absent on very acid soils or soils devoid of calcium. It appears that in general they are not much affected by soil acidity unless it falls below *p*H 4·5. Thus, C. H. Bornebusch[1] found they flourished in Danish forest soils, such as mull soils under beech or oak when the *p*H was between 5 and 5·5, though not if it was below *p*H 4·5. A. Stöckli[2] found casting species active in Swiss forest soils with *p*H between 4·7 and 5·2, and confirmed E. J. Salisbury's[3] finding that, in these acid conditions, their excreta was over half a *p*H unit higher than the soil they were working in. H. L. Richardson[4] found casting species very active in Rothamsted pasture plots of *p*H 4·7 and above, though they were almost absent in plots of *p*H 4, and he made the further very interesting observations that moles, whose principal diet is worms, and probably mainly *L. terrestris*, apparently will not follow them into soils with a *p*H below 5·5, suggesting that *L. terrestris* is more sensitive to acidity than *A. nocturna* or *A. longa*. Bornebusch further found that if the *p*H of the soil was under 4·5, whether it was a mull or a mor soil, the total weight of earthworms was only a small fraction of what it was in the less acid soils, and only very small species were present, which lived in the surface litter.

Earthworms, where they flourish, as in virgin soils and pastures, are important agents in mixing the dead surface litter with the main body of the soil. They drag down leaves and other litter into their burrows, so making them more accessible to attack by the soil micro-organisms. Peat formation is, in fact, typical of uncultivated land too acid for earthworms; thus at Rothamsted a mat of dead vegetation is accumulating on all the pasture plots whose *p*H is below 4, apparently solely

[1] *Forstl. Forsoegsv. Danmark*, 1930, **11**, 1.
[2] *Landw. Jahrb. Schweiz.*, 1928, **42**, 1.
[3] *J. Linn. Soc.* (*Botany*), 1924, **46**, 415.
[4] *J. Agric. Sci.*, 1938, **28**, 73.

because there are no earthworms or other animals capable of mixing this debris into the body of the soil.

Earthworms improve the aeration of a soil in two ways. They are very extensive channellers and burrowers, and these channels serve to improve the drainage of the surface soil, to give regions of good aeration and to loosen the whole soil throughout the zone in which they are working. They are most active in the surface layers of the soil, rarely working the soil intensively below 6 to 8 inches, though a few species will make burrows to much greater depths which often serve as passages for plant roots to penetrate into the subsoil. They can also play an important role in irrigated fields, for N. A. Dimo[1] found up to six million channels per acre coming to the soil surface in fields of irrigated lucerne; and these allow the irrigation water to penetrate rapidly through the surface layers of the soil into the subsoil.

They also improve the aeration and at the same time the water-holding power of the actual soil crumbs, for the outstanding action of the earthworm is to ingest soil particles along with the organic matter, grind up the organic matter with the soil particles in its gizzard in the presence of calcium carbonate secreted by some of its digestive glands, and excrete this calcium-saturated intimate mixture of organic matter and soil as a blackish-brown mould or loam. This mould, which in most soils is probably only produced by earthworms, is admirably suited for plant growth, having a very desirable air-water régime. On the lighter soils it has a considerably higher water-holding power than the soil itself, and on the heavier is more mellow and has a very favourable structure.

However, a word of warning must be given here. These remarks only apply when casting species of worms, in Great Britain *A. nocturna* and *A. longa*, are numerous. Thus A. C. Evans[2] found at Rothamsted that the top few inches of pasture soil had a pore space of 67 per cent when these were dominant, but only one of 40 per cent when they were absent, even though the total weight of worms was about the same on the two fields. Further, he also found that where casting species were dominant the surface soil was rather higher in silt and clay, and lower in coarse sand than the subsurface, and this would increase the water-holding power of the surface soil. Again, as will be mentioned on p. 416, A. K. Dutt[3] and R. J. Swaby found that worm-casts only possessed a stable structure if they were produced on pasture soils; they had this property to a much less extent when produced on arable soils.

The chemical composition of wormcasts differs from that of the soil mass because the worms feed selectively on the material in the soil,

[1] *Pedology*, 1938, No. 4, 494. [2] *Ann. Appl. Biol.* 1948, **35**, 1. [3] *J. Amer. Soc. Agric.*, 1948, **40**, 407.

concentrating in the cast most of the nitrogen and mineral constituents present in the organic matter ingested. Thus, the casts are richer in available plant nutrients than the soil, as is shown by some results of H. A. Lunt and H. G. M. Jacobson[1] given in Table 39. This effect is due to the breakdown of the organic matter by the worms or by the microflora in their gut and, for as far as plants growing on the soil are concerned, could equally well be brought by the soil microflora, provided a mechanism was available for mixing up the organic matter with the soil. There is no evidence yet that the passage of inorganic soil particles through the worm's alimentary canal affects the availability of the plant nutrients they contain, nor is there any need to assume the existence of this effect, for, as Lunt and Jacobson point out, the wormcasts are poorer in plant nutrients than the original litter.

TABLE 39

The Chemical Composition of Wormcasts compared with that of the Whole Soil (Connecticut)

Depth of sample	Arable soil			Forest soil (mean of 4 soils)			
	Cast	0–6 in.	8–16 in.	Cast	A1	A3	B
	In parts per million of soil						
Exchangeable calcium	2790	1990	481	3940	747	155	171
Exchangeable magnesium	492	162	69	418	140	43	59
Exchangeable potassium	358	32	27	230	138	32	25
Available phosphorus	67	9	8	9	7	3	3
Nitrate nitrogen	21·9	4·7	1·7	—	—	—	—
Total carbon in per cent	5·17	3·35	1·11	15·6	5·9	2·1	1·0
Total nitrogen in per cent	0·353	0·246	0·081	0·625	0·327	0·130	0·064
C/N	14·7	13·8	13·8	25·1	18·0	16·3	15·0
pH	7·0	6·4	6·0	5·3	4·6	4·6	4·7
Per cent of base saturation	93	74	55	63	32	18	12

There is still much uncertainty whether earthworms directly affect the fertility of soils. As long ago as 1910 E. J. Russell[2] showed that crop growth was improved if dead earthworms were added to the soil, and that their bodies nitrified very quickly, but he could not show that living earthworms affected the growth of the crop. A. C. Evans has recently reinvestigated this problem and could not show that living worms increased the green weight of crops growing in the soil, though they appeared to increase its dry weight, a result that is difficult to interpret, but one that could be due to the improved physical condition

[1] *Soil Sci.*, 1944, **58**, 367.

[2] *J. Agric. Sci.*, 1910, **3**, 246. For additional confirmation, see B. Lindquist, *Svensk. SkogsvFören Tidskr.*, 1941, **39**, 179. H. Hopp and C. S. Slater, *J. Agric. Res.*, 1949, **78**, 325, also confirmed most of these conclusions.

of the soil. An observation of Hopp and Slater[1] is in accord with this conclusion, for they found that either active earthworms (*A. caliginosa*) or an infestation of ants living in tubs of a loam soil planted to a grass-clover mixture, increased the proportion of clover to grass. The direct effect of worm activity on plant growth must still, therefore, be considered unsettled, though the effect, if it exists, cannot be large.

Darwin first drew attention to the great quantity of soil earthworms can move a year; he estimated that the earthworms on some pastures outside his house could form a new layer of soil 7 inches thick in thirty years, or that they brought up about 20 tons of soil per acre, enough to form a layer 0·2 inch deep each year. This figure represents fairly well the amount of earth the casting species of earthworms can put on the soil surface every year. Thus, A. Stöckli found a similar figure in some Swiss, and A. C. Evans in some Rothamsted, pastures. It is not yet possible to estimate from what depth the soil cast on the surface has been derived, but most of it has probably come from the top 4 to 6 inches.

This figure, however, does not represent the total amount of soil that passes through the gut of the earthworms each year, for this has been derived purely from the casting species. No attempt has yet been made to measure this accurately, but A. C. Evans[2] has made a rough estimate by assuming the weight of wormcasts produced by worms is proportional to the weight of the worms. His results for some Rothamsted fields with different cropping histories are given in Table 40, and show that some fields have high earthworm activity although

TABLE 40

Estimated Consumption of Soil by Worms at Rothamsted

Cropping of Field	Number of worms thousands/acre		Weight of worms	Worm casts	Soil excreted below ground	Total soil consumption
	A. nocturna and *A. longa*	Others	lb./acre	tons/acre	tons/acre	tons/acre
Old pasture (1)	340	430	880	25	12	36
(2)	140	170	540	11	9	20
Established leys:						
18 years old	120	130	500	12	10	21
8 years old	30	330	660	2	21	23
5 years old out of woodland	50	190	650	2	17	19
5 years arable after old pasture	30	130	120	3	2	5

[1] *J. Agric. Res.*, 1949, **78**, 325. [2] *Ann. Appl. Biol.*, 1948, **35**, 1.

few casting species are present, so only very few wormcasts are produced. *A. nocturna* and *A. longa* are the casting species present, so their numbers are given separately. The table also shows that normal arable soils have a low earthworm activity compared with established leys and pastures.

Earthworms, such as *L. terrestris*, have a second effect on soil transport, for they also excrete surface soil into their deeper burrows, but the amount of surface soil they transport into the subsoil is probably small.

Arable conditions discourage the larger worms much more than the smaller, both because of the disturbance due to cultivations themselves and also of the comparative scarcity of suitable food. Nor is there any evidence that they have any important effect in the soil, for the cultivation operations themselves mix the plant debris with the soil particles and help to maintain good aeration. It has not yet been established if the earthworms present in arable soils have any appreciable influence on the type of humus produced from the plant debris added to the soil. These remarks apply to British conditions. It is just possible they may not apply in areas with warm wet summers. Thus H. Hopp and H. T. Homer,[1] working in Maryland, found their arable soil contains up to 500 lb. of earthworms per acre, and that a two year rotation of wheat and seeds (i.e. a grass or lespedeza ley) or continuous soybeans with regular applications of a surface mulch has about the same number and weight of earthworms as a contiguous old pasture.

One can summarise our present knowledge on the importance of earthworms in agriculture as follows. They are of very great importance in undisturbed forest and pasture soils above *p*H 4·5, for they are the principal agents in mixing dead plant debris on the surface of the soil with the soil itself, and in doing this they help to keep the surface soil loose and well aerated. They may also play an important role in the conversion of plant litter into humus, as their gut may form a favourable environment for the necessary chemical changes to take place, but this has not yet been rigorously proved. Only two British species produce wormcasts on the surface of the soil, all the rest excreting in the soil itself.

Arthropods

The common soil arthropods belong to a restricted number of orders, of which the acarine mites among the arachnids, the millepedes (*Diplopoda*) and centipedes (*Chilopoda*) among the myriapods, and the springtails (*Collembola*) the larvae of beetles (*Coleoptera*) and of dipterous flies, ants and termites among the insects are the most numerous.

[1] *J. Soil and Water Conserv.*, 1946, **1**, 85. See also H. Hopp, *Proc. Soil Sci. Soc. Amer.*, 1948, **12**, 503.

The greater proportion of the mites feed either on dead or decaying plant tissues, or on fungi,[1] and the rest are probably predaceous. A. P. Jacot[2] describes how many of these mites, about 0·1 to 1 mm. in length, feed on the inside of dead plant roots, leaving a channel lined with the outer corky layer of the root. He also stresses the fact that as many of them are adapted for burrowing they must, by virtue of their numbers, play an important role in keeping the soil open and aerated.

The myriapods consist mainly of millepedes with a smaller number of centipedes. The millepedes appear to thrive in somewhat the same soils as the earthworms, and if the Broadbalk figures, given in Table 37, are at all representative of arable soils, they may form a large part of the total weight of the soil fauna. They feed on decaying plant remains and probably on fungal mycelium, though some feed on living plants, particularly if the amount of decomposable organic matter falls too low. A few ingest soil particles along with their food, and may produce excrement similar in properties, though not in shape, to wormcasts.[3] The centipedes are much more active than the millepedes, and are predaceous on millepedes, earthworms and other larger members of the soil fauna. Smaller myriapods, such as pauropods and symphylids, may occur in comparable numbers, but their contribution to the total weight of myriapods is probably small.

The wood-lice—isopods—are predominantly saprophagous or phytophagous, but their relative importance in the decay of organic matter and in altering the soil structure is unknown, though their gut may be a favourable environment for the humification of plant residues to take place.[4] They probably often thrive in sites too dry for earthworms. Thus N. A. Dimo[5] has shown that they may be very active channellers and burrowers during the summer in semi-desert soils, that is, during a period when the earthworms are aestivating. He found them burrowing down to 2 to 3 feet and bringing up during the season about 2 tons of soil per acre in a condition of small crumbs with a mellow structure.

The springtails are usually numerically the most important members of the insects. They are minute wingless insects, about 0·5 to 2 mm. long, and feed on decaying organic matter. Their population usually contains a high proportion of immature forms, so that they probably form an important source of food for predators. But, in spite of their numbers, they are probably less important than the much larger beetle larvae. These larvae are important soil burrowers and are typically

[1] K. H. Forsslund, *Medd. Skogsförsöksanst.*, 1938, **31**, 87; 1945, **34**, 1.
[2] *Ecology*, 1936, **17**, 359; *Quart. Rev. Biol.*, 1940, **15**, 28.
[3] L. G. Romell, *Ecology*, 1935, **16**, 67; T. H. Eaton, *Amer. Midl. Nat.*, 1943, **29**, 713.
[4] H. Franz, *Bodenk. PflErnähr.*, 1943, **32**, 336. [5] *Pedology*, 1945, No. 2, 115.

saprophagous or coprophagous, though some, such as wireworms, which are larvae of elaterid beetles, predominately of the genus *Agriotes*, attack living plants. The larvae of the dipterous flies are again mainly saprophagous, though little is known of their effect on the soil. Ants may be of great local importance as soil movers,[1] particularly in the tropics, but they normally take great care not to mix any organic matter with the soil they move. Termites in many tropical soils seem to be the predominant animals affecting the soil and the plant.[2] There are many common soil species which move large quantities of soil, sometimes ingesting much of what they move, and bringing grass and other plant material into the soil and burrowing and tunnelling through the soil in the process. Some soil termites often appear, in fact, to be the tropical analogue of the earthworm. But little is yet known about the detailed ecology of these large populations or of how they fit into the general picture of the animal life of the soil.

Gasteropods

Slugs and snails are the two soil representatives of the Gasteropods, and so far little is known about their distribution or numbers. Most are surface feeders, usually active in damp conditions, hence either burrow into the soil or into a dense, shady spot, such as under stones or leaves or in thick grass tussocks during the day. H. F. Barnes and J. W. Weil[3] have found that the food of slugs is mainly dying vegetation, such as freshly fallen leaves, fallen and old grass, and so on, and that they mainly attack the actively growing parts of plants only when other food is scarce. They are therefore typically scavengers rendering old plant tissues more usable by the smaller members of the animal population by excreting them in a macerated and partially digested form. Some slugs, such as species of *Testacella*, are predaceous on other slugs, worms and centipedes.

Normally, the numbers of slugs on arable land is not very high, though in some areas they may damage potatoes. However, D. C. Thomas[4] has given an example of a wheat field carrying 600,000 slugs per acre and weighing about 400 lb., which is equivalent to about two sheep, but they are only serious pests in gardens and market gardens. The numbers are generally higher on pasture and forest soils than on arable, but even in a good mull soil Bornebusch[5] found that slugs did

[1] For illustrations, see J. Thorp, *Sci. Mon.*, 1949, **68**, 180.

[2] For a general description of the effect of termites on soil fertility, see A. M. Adamson, *Trop. Agric. Trin.*, 1943, **20**, 107; W. V. Harris, *E. Afric. Agric. J.*, 1940, **6**, 62; H. Wilkinson, ibid., 67.

[3] *J. Animal Ecol.*, 1944, **13**, 140; 1945, **14**, 71. I must also thank Dr. Barnes for the help he has given me with this section.

[4] *Ann. Appl. Biol.*, 1944, **31**, 163; 1947, **34**, 246. [5] *Forstl. Forsoegsv. Danmark*, 1930, **11**, 1.

not contribute more than 7 to 8 per cent either by weight of the population or to the animal oxygen requirement.

The Soil-inhabiting Mammals

Animals of the mouse family—mice, voles and shrews—and moles are present in appreciable numbers in some undisturbed soils, such as forest and prairie soils, and to a less extent in some pastures. Though their total weight per acre is only small, probably under 5 lb. in forest soils[1] and up to 10 lb. on open ranges,[2] they can cause a very important loosening of the surface layers of the soil by honeycombing it with their burrows and nests, and many of them also transport an appreciable amount of sub-surface or subsoil and leave it on the soil surface as mounds.[3] Some semi-arid soils can also carry a population of mammals that burrow into the deeper subsoil, and these burrows may be filled in course of time with surface soil rich in humus. Thus, these soils have numerous channels of dark soil running in the lighter humus-poor subsoil as is shown, for example, in Plate XXX.

[1] W. J. Hamilton and D. B. Cook, *J. Forestry*, 1940, **38**, 468.
[2] W. P. Taylor, *Ecology*, 1935, **16**, 127.
[3] For detailed examples, see W. J. Hamilton, *Bull. New York Zool. Soc.*, 1940, **43**, 171; J. Thorp, *Sci. Mon.*, 1949, **68**, 180.

CHAPTER XII

THE GENERAL ECOLOGY OF THE SOIL POPULATION

THE VARIOUS GROUPS of soil organisms do not live independently of each other, but form an interlocked system more or less in equilibrium with the environment. This is obviously true for the predators, but it is equally true for the saprophytic species, for they are all competing for the available food supply, and each has developed a series of symbiotic and antibiotic relations with its neighbours for increasing its ability to get its share of the available food. Thus the composition of the population in any soil achieves a certain equilibrium which depends on the environment; and for any particular soil farmed on a definite system the equilibrium is fairly stable. The soil, in fact, usually appears to be fairly "well-buffered" biologically. Hence, if any particular soil-inhabiting organism is absent from a soil it cannot usually be made an active component of the soil population merely by inoculating it into the soil;[1] it can only be introduced by altering the environment either through the crops grown on the soil, the energy-containing material added to the soil, or the general environmental conditions of life in the soil itself. This limitation naturally applies with much less force if the organism has a close relationship with any of the crops growing on the soil.

This stability of the population naturally refers to the conditions holding under normal conditions: it may be upset when new sources of energy-material, such as plant debris, composts or farmyard manures are added to the soil, for these additions can cause a rapid, though temporary, rise in certain groups, particularly some of the fungi.

The Distribution of Micro-organisms through the Soil Space

The soil micro-organisms are not uniformly distributed throughout the soil; the fungi congregate round particles of decaying plant and animal debris, and the bacteria live on these as well as on the surface of soil particles.[2] P. C. O. Jones and J. E. Mollison,[3] using their direct staining technique, were able to show that the bacteria are present in colonies or clumps as is shown in Plate VII, and the proportion of

[1] For an example of an attempt to do this, see S. A. Waksman and H. B. Woodruff *Soil Sci.*, 1940, **50**, 421.

[2] C. Rouschal and S. Strugger, *Naturwiss.*, 1943, **31**, 300; *Canad. J. Res.*, 1948, **26** C, 188.

[3] *J. Gen. Microbiol.*, 1948, **2**, 54.

clumps containing, say, n bacteria in the soil is proportional to x^n/n, where x is a number smaller than unity and depends on the population. Thus, the distribution of bacterial colonies and of bacteria in the colonies found in the soil of the permanent mangold field at Rothamsted is as follows:

Number of bacteria in the colony	1	2	3	4	5	6	7 and over
Observed proportion of colonies in the population	51	23	8	7	3	2	5
Calculated proportion of colonies in the population	53	20	10	6	4	2	5
Observed proportion of bacteria present in colonies of each size	23	21	11	12	7	6	21

These figures actually refer to the plot receiving 14 tons of farmyard manure per acre per annum, but the figures are almost identical for the unmanured plot and for a plot receiving only fertilisers which has the same average yield of mangolds as the farmyard manure plot. Thus, this distribution may be characteristic of a soil and not strikingly dependent on the manurial treatment.

The Rossi-Cholodny slide technique has been the method most extensively used for investigating the distribution of the soil micro-organisms. The technique consists in burying a microscope cover-slip in the soil, leaving it there for a certain time and then digging it up; and it is based on the assumption that the organisms developing on the slip are representative of those in the soil. This is only true if the slip can be buried in such a way that the distribution of pockets of good, medium and poor aeration on the surface of the slip is about the same as in the undisturbed soil—a condition whose fulfilment is difficult to guarantee—and if the organisms developing on the slip do not have a preference for growing on a continuous surface.

The results obtained by using this technique are entirely concordant with other knowledge, and will be described for three conditions—in fallow soil, in soil carrying a crop, and in soil to which fermentable organic matter has been added.

In a fallow soil[1] only a sparse population develops on the slips, extensive development only taking place near pieces of organic matter. The bacteria seem to be mainly small organisms in small colonies, which appear to be pure cultures of the organisms and which may be compact or loose and composed of cocci or short rods. A few of the looser colonies often contain rather longer rods, all lying more or less

[1] See, for example, R. L. Starkey, *Soil Sci.*, 1938, **45**, 207.

parallel to each other. There are a number of isolated bacteria, commonly short rods, scattered over the slide, long rods are scarce and usually occur near pieces of organic matter, and the larger cells commonly occur in clusters of two to four. Actinomycetes are fairly common, usually occurring as a line of spores, or conidia, each about the size of small coccus or coccoid rod, and hence indistinguishable from them if occurring individually. Fungal mycelium is rare, and this often is attacked by bacteria.

In cropped land the population does not differ in kind but becomes more numerous. Extensive bacterial development occurs around some plant rootlets, the colonies of coccoid or short rods becoming so dense that they cannot be resolved into their constituent organisms under the microscope. Actinomycetes in particular, and fungal mycelium to some extent, share in this general development, though they are not conspicuous in the immediate neighbourhood of the rootlets.

The effect of adding fermentable organic matter can easily be seen. The population becomes much more dense, and typical groups of bacteria develop. Thus, adding sugars can give many Azotobacter-like colonies appearing on the slide, and adding cellulose many typical Cytophaga-like bacteria. This initial bacterial attack is often followed by development of fungi and actinomycetes, which are later attacked by other bacteria.[1] In acid soils, or when some types of organic material resistant to decomposition are added, fungi develop initially, but decomposition is slower than when bacterial development begins. Thus, fungal mycelia can often be seen radiating from pieces of decomposing organic matter, though after a few weeks' decomposition the fungi may be mainly represented by spores.[2] But fungi, being large micro-organisms, can be seen directly in the soil with a suitable microscope and their development followed. W. Kubiena and C. E. Renn,[3] for example, followed the development of different groups of fungi when various substances were added to the soil, and showed that the species developing depended on the air supply, so that the fungal flora was not the same inside as on the surface of the soil crumbs.

W. Kubiena[4] has stressed the control which the size of the soil pores has on the development of the soil fungi; typically these spores and fruiting bodies are smaller, and sometimes much smaller, in the soil where space is restricted than in pure cultures where there is no such restriction. This dwarfing effect of the soil pore-space on the size of organisms affects protozoa and diatoms; thus, both he and M. Koffmann[5] found the largest ciliates present in the soil were only 18 to 22 μ in size, whereas they often attain 60 μ in cultures. This control is

[1] J. Ziemiecka, *Zbl. Bakt.* II, 1935, **91**, 379.
[2] H. L. Jensen, *Proc. Linn. Soc., N.S.W.*, 1934, **59**, 200.
[3] *Zbl. Bakt.* II, 1935, **91**, 267.
[4] *Micropedology*, Ames, 1938.
[5] *Arch. Mikrobiol.*, 1934, **5**, 246.

naturally not effective for those organisms possessing the power of increasing the pore size, such as the burrowing and channelling invertebrates.

The weight of the different organisms in the soil cannot yet be determined accurately, largely because of the great uncertainty in the weight of the individual organisms. A Rothamsted arable soil containing 3 per cent organic matter, or, say, 60,000 lb. per acre of dry organic matter in the top 6 inches of soil, will contain about 3,000 million bacteria or similar sized cells and about 30,000 flagellates and 20,000 amoebae. The average volume of a soil bacterium is unknown, but it is unlikely to exceed $0{\cdot}5\mu^3$ or to be less than $0{\cdot}2\mu^3$.[1] If the former figure is taken, the weight of bacteria in the top 6 inches of an acre of soil will be about 3,500 lb., and if the latter about 1,500 lb. live weight. Assuming the cells have 20 per cent dry matter, these will represent 700 and 300 lb. of dry organic matter per acre, or between $\frac{1}{2}$ and 1 per cent of the total organic matter in the soil. The amount of dry matter in the fungal hyphae and spores is not known, but if one assumes that there is about 40 metres of mycelium per gram of soil, as suggested in Table 42, and this has an average diameter of 5 μ, there will be about 1,500 lb. of fungal mycelium per acre, if it is all alive. However, a proportion of this is undoubtedly dead, so the organic matter content of the mycelium will probably be less. But a dry weight of 300 lb. per acre is possible, which is comparable to that of the bacterial. A rough calculation gives the weight of protozoa as about 150 lb. per acre live weight, or 30 lb. per acre dry matter, and Table 37 suggests that the soil fauna, excluding the protozoa and nematodes, have a dry weight of 100 to 200 lb. per acre. Therefore a very rough calculation indicates that the weight of the dry matter in the soil population in an arable soil may be of the order of 1,000 lb. per acre, or something between 1 and 2 per cent of the organic matter.

The Effect of the Energy Supply

The general requirements of the soil organisms are the same as those of plants: energy, nutrients, water, suitable temperatures and the absence of harmful conditions. The great difference between them is the source of energy; green plants derive their energy directly from sunlight, and the soil organisms—apart from the photosynthetic forms —obtain theirs either directly or indirectly from the products of plant metabolism. The size of the soil population is thus controlled by the rate at which energy-containing material synthesised by plants is added to the soil.

[1] For a justification of this figure, I. V. Tiurin, *Pedology*, 1946, 11.

The organisms derive their energy in different ways from the added plant tissues; some attack the dead or dying plant tissues, or even the tissues of the living plant, and these form the primary source of energy for the remainder of the population, which is either predaceous on them while alive or else lives on the waste products of their metabolism or on their dead bodies. The number, or the activity, of the micro-organisms is controlled by the amount of energy that can be released by the decomposition of the added organic matter and, no matter how many stages or what organisms are involved in its degradation, only a certain definite amount of energy can be extracted; and this amount cannot exceed the energy set free when the organic matter is completely oxidised.

The energy in the organic matter differs fundamentally from the nutrients in it. Nutrients can be used over and over again by an unending succession of organisms. An atom of nitrogen never loses its value; it might in the course of a single day form part of a fungus, a bacillus which decomposed it, an amoeba which ate the bacillus, and a bacterium which decomposed the dead amoeba; for all these organisms one and the same atom of nitrogen would be a perfectly good nutrient.

But energy cannot be used in this way. It is as indestructible as matter, but once transformed to heat, it cannot be used by micro-organisms or any other living things; whatever energy is dissipated by one organism becomes out of reach of the others. It follows, therefore, that no factor affecting the trophic life in the soil which does not add to the stock of energy material can permanently increase the numbers of all the groups; if one group increases, others necessarily decrease.

The supply of energy and the turnover of nutrients thus become the chief factors determining the kinds and numbers of organisms in the soil. An exact measure of the amount of energy available to micro-organisms in a given weight of soil cannot yet be made, though the amount of energy transformed in a given period can be estimated by determining the total quantities at the beginning and at the end. Estimates obtained from analytical data for two of the Broadbalk plots are given for illustration only in Table 41.

This great increase in the amount of energy dissipated in the two plots is barely reflected in the numbers of micro-organisms present in the soil, for whereas the farmyard manure plot is dissipating fifteen times as much energy each year as the unmanured, or as the neighbouring plots receiving fertilisers only, yet it has scarcely twice as many bacteria or protozoa, and only about the same number of fungi, as these plots, as can be seen in Table 42. Only the protozoa seem to be really dependent on the fertility of the soil, in the sense that their active numbers roughly follow the average wheat yield.

TABLE 41

Annual Energy Changes in Soil: Broadbalk

Approximate estimates only

Millions of kilo-calories per acre per annum

	Farmyard manure added	No manure added
Added in manure	14	Nil
Added in stubble	2	0·3
Total added	16	0·3
Net loss from soil	Nil	0·5–1
Stored in soil	0·5–1	Nil
Dissipated per annum	15	1
Per day: Calories	41,000	2,700
Equivalent to the requirements of	12 men	¾ man
The human food grown provides for	2 men	½ man

TABLE 42

The Effect of Long-continued Applications of Farmyard Manure and Fertilisers on the Numbers of Micro-organisms in some Broadbalk plots[1]

Numbers per gram of air-dry soil

Mean of six determinations made at monthly intervals from 20-1-48 to 23-6-48

Treatment	Unmanured	Complete fertiliser	Farmyard manure
Plot number	3	7	2
Number of bacteria			
Total cells in thousand millions	1·6	1·6	2·9
On plates in millions	50	47	67
Number of Fungi			
Pieces of mycelium in millions	0·85	0·94	1·01
Length of mycelia in metres	38	41	47
On plates in millions	0·16	0·26	0·23
Number of Protozoa			
Total in thousands	17	48	72
Active in thousands	10	40	52

[1] Unpublished observations of P. C. O. Jones, J. E. Mollison, and F. A. Skinner. I am much indebted to these workers for permission to use their data. The data for protozoa have been published by B. N. Singh, *J. Gen. Microbiol.*, 1949, **3**, 204.

Clearly, the organisms on the farmyard manure plot must be living much more actively than on the other plots, presumably due to them passing a smaller proportion of their time in resting stages.

So far as present knowledge goes, the soil organisms are living right up to their income in the matter of nutrients and energy supply. Any increase in the available organic matter capable of supplying energy at once increases the numbers of micro-organisms. Further, it appears to be a fairly general rule that, under natural conditions, the greater the number of soil-inhabiting organisms in a soil, the greater the number of species present, but this generalisation has not yet been adequately tested.

The Activity of the Soil Population

The numbers of micro-organisms in a soil give no direct measure of the activity of the microbial population. The activity of the population is not a concept that can be given a quantitative definition, but for many purposes it can be measured by the amounts of either CO_2 or heat evolved by the population, that is, by the rate at which either the oxidisable carbon compounds or the energy available for organic growth are being dissipated. Neither of these definitions give a perfect measure of the activity, for there is no necessary connection between the heat or CO_2 evolution of an organism and the amount of growth it makes; nor, in fact, are these two definitions always concordant, for the amount of CO_2 produced per calorie evolved increases as the oxygen tension decreases because energy-rich materials are then being either stored in or lost from the soil.

The activity of the soil population has usually been measured by the rate of CO_2 evolution of the soil. Scarcely any measurements have been made of the heat evolution in soils, though F. H. H. van Suchtelen[1] suggested this approach in 1923; with modern thermometric apparatus it should present no great technical difficulties.[2] The CO_2 evolution is usually measured by incubating a sample of the soil in the laboratory and determining the amount of CO_2 given off. One can measure the CO_2 content of the soil air in the field quite easily, but this does not give a direct measure of the amount of CO_2 evolved.

In general, the CO_2 evolution increases as the number of bacteria increases. D. Fehér[3] found a close correspondence between the bacterial numbers, as determined by the plating technique, and the CO_2 evolution at different seasons of the year for different soils, and concluded that the activity of the whole population rose and fell with the

[1] *Zbl. Bakt.* II, 1923, **58**, 413; 1927, **71**, 53; 1929, **79**, 108.

[2] A. S. Newman and A. G. Norman (*Proc. Soil Sci. Soc. Amer.*, 1944, **8**, 250) have recently discussed some of the precautions that must be taken when this technique is used.

[3] *Arch. Mikrobiol.*, 1934, **5**, 421; 1938, **9**, 193.

numbers of bacteria so determined. But H. L. Jensen[1] found the CO_2 evolution was poorly correlated with the bacterial numbers so determined, but was sometimes well correlated with them when determined by the total cell count. The only conditions when the fungi seemed to contribute appreciably to the CO_2 evolution was when there was a vigorous growth of mycelium on buried Cholodny slides, and this occurred for only one or two weeks after fermentable organic matter was added to the soil.

The Relation between Microbiological Activity and Soil Fertility

In the early days it was often noted that fertile soils had higher bacterial numbers, often higher nitrate contents and higher CO_2 evolution than infertile,[2] and many attempts were made to measure soil fertility by some simple procedure based on this result. There certainly can be a connection between bacterial numbers, CO_2 evolution and soil fertility.[3] Thus, H. G. Thornton and P. H. H. Gray[4] found a good correlation between bacterial numbers, determined by the total cell count method, and the yield of barley straw on some plots on Hoosfield, the permanent barley field at Rothamsted, as is shown in Fig. 16. But no general correlation between bacterial numbers and crop yields has been found even at Rothamsted, for Table 42 on p. 191 showed that the total cell counts of bacteria on Broadbalk do not follow yields at all: Plot 3 and Plot 7 have about the same cell count, yet in the last 10 years Plot 7 has had an average yield of wheat more than double that on the unmanured. Nor would a close correlation be expected, for the fertility of a soil is a very complex property, and the various factors contributing to it affect the microbiological activity in different ways.

However, the activity of certain groups of organisms can be used to measure the contribution of selected factors to the fertility of a soil. Thus, *Azotobacter*, which is sensitive to calcium and phosphate deficiencies, can be used to determine a deficiency of either of these.[5] Other organisms have also been used for measuring the phosphate status of a soil, such as the fungus *Aspergillus niger*[6] and suitable species of

[1] *Proc. Linn. Soc., N.S.W.*, 1936, **61**, 27.

[2] E. J. Russell, *J. Agric. Sci.*, 1905, **1**, 261; with A. Appleyard, ibid., 1915, **7**, 1.

[3] J. R. Neller, *Soil Sci.*, 1920, **10**, 29; S. A. Waksman and R. L. Starkey, *Soil Sci.*, 1924, **17**, 141.

[4] *Proc. Roy. Soc.*, 1934, **115** B, 522.

[5] H. R. Christensen and O. H. Larsen, *Zbl. Bakt.* II, 1911, **29**, 347; *Soil Sci.*, 1923, **15**, 329. Another technique using *Azotobacter* was developed by S. Winogradsky and J. Ziemiecka, *Ann. Inst. Pasteur*, 1928, **42**, 36. For an application of this technique to Rothamsted soils, see J. Ziemiecka, *J. Agric. Sci.*, 1932, **22**, 797.

[6] A. Niklas, *Ztschr. Pflanz. Düng.*, 1933, A **32**, 50; R. Martin, *Ann. Agron.*, 1943, **13**, 27.

Cunninghamella,[1] and the use of *Aspergillus niger* has also been suggested for measuring the amount of available copper in the soil.[2]

Symbiotic and Antibiotic Relations between the Microflora

The various groups of soil organisms do not live independently of each other; they form an interlocked system more or less in equilibrium in a given soil, and most organisms have developed a series of symbiotic and antibiotic relations with their neighbours.

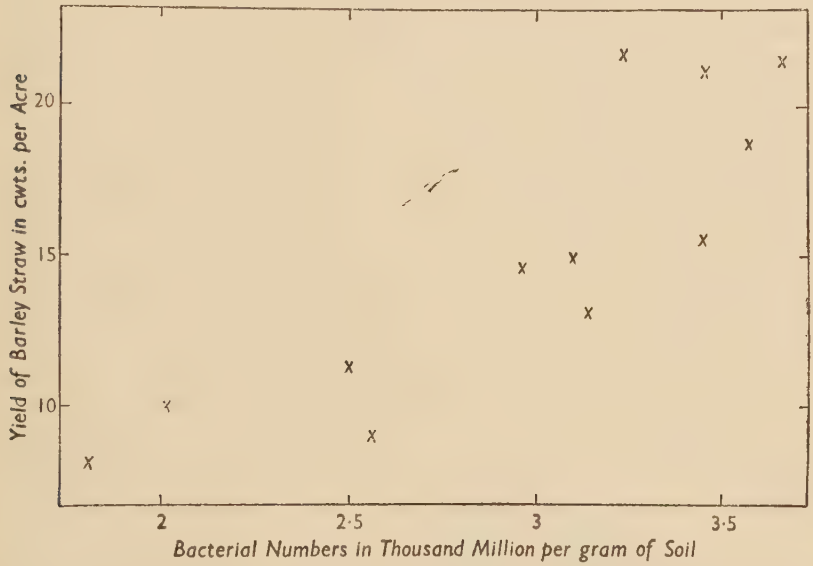


FIG. 16. Relation between bacterial numbers, determined by total cell count and the yield of barley straw on differently manured plots on Hoosfield.

Some, perhaps the majority, of the soil's microflora have complex nutritional requirements, but organisms can often obtain their necessary growth-promoting substances from other groups that either excrete them naturally or can be induced to excrete them for their benefit. W. F. Muller and W. H. Schopfer[3] have given a very beautiful illustration of this, using the two fungi *Mucor Ramannianus* and *Rhodotorula rubra*. The former needs either vitamin B_1 or the thiazole part of the molecule, for it can synthesise the pyrimidine part itself, and the latter needs either vitamin B_1 or the pyrimidine part, for it can synthesise the thiazole part. These two can grow luxuriantly together in a vitamin-free medium, each synthesising and supplying to the other that part of the vitamin B_1 molecule that it lacks. This is purely

[1] A. Mehlich, E. B. Fred and E. Truog, *Soil Sci.*, 1934, **38**, 445.
[2] J. Smit, *Proc. 3rd Int. Congr. Microbiol.*, New York, 1939, 693. [3] *C.R.*, 1937, **205**, 687.

artificial symbiosis which does not occur naturally, but A. G. Lochhead and F. E. Chase[1] have shown that filtrates from common soil bacteria with very simple nutrient requirements can supply the needs of other common soil bacteria with complex requirements. There is ample opportunity for these nutrient transfers to take place in the soil between different members of the population, though the symbiotic relations between the soil organisms are probably unspecialised, that is, any one organism can probably obtain its essential nutrients from a wide rather than a restricted range of other organisms.

Two other types of beneficial interactions are presumably occurring in the soil. Two organisms may be living together by one using the excretion products of the other; and this will probably occur more commonly when the air or nitrogen supply is restricted, for then a greater proportion of the ingested carbon is usually excreted. Again, two organisms living together can sometimes effect a decomposition neither can do when growing alone. Many examples have been given of two soil organisms carrying out a decomposition much quicker when growing together than when alone,[2] but few, if any, of the extreme case.

Other soil organisms develop antibiotic relations with selected species,[3] which are brought about by their excreting substances into the soil solution that prevent the affected organisms from growing or that kill them by lysis, that is, by dissolving their outer membrane. The fungus *Penicillium notatum* is such an organism: it excretes penicillin which lyses the cells of many bacterial groups. The ability to produce antibiotics is not confined to fungi, for it is also strongly developed by many actinomycetes and bacteria. At least half the soil fungi and actinomycetes probably produce such substances,[4] but the proportion of bacteria producing them is probably much smaller. The substances so far recognised usually act only on other members of these three groups, but there are some bacteria, such as *Pseudomonas aeruginosa* and *Ps. pyocyanea*, which produce substances that can kill species of soil protozoa belonging to the amoebae, flagellates and ciliates.[5] These substances appear to have very varied chemical composition and are often called after the organism producing it, as, for example, penicillin, mentioned above.

It is not yet known how far the power of producing these lytic substances goes hand in hand with the power of feeding on the lysed

[1] *Soil Sci.*, 1943, **55**, 185.

[2] See, for example, A. G. Norman, *Ann. Appl. Biol.*, 1930, **17**, 575, and S. A. Waksman and I. J. Hutchings, *Soil Sci.*, 1937, **43**, 77. For an example when one bacterium is a cellulose decomposer, see L. Enebo, *Nature*, 1949, **163**, 805.

[3] S. A. Waksman, *Soil Sci.*, 1937, **43**, 51, and *Bact. Rev.*, 1941, **5**, 231, has given full historical reviews of the development of these ideas and has described many examples of this antibiosis. See also his book *Microbial Antagonisms and Antibiotic Substances*, 2nd ed., New York, 1947.

[4] R. L. Emerson *et al.*, *J. Bact.*, 1946, **52**, 357.

[5] B. N. Singh, *Nature*, 1942, **149**, 168; *Brit. J. Expt. Path.*, 1945, **26**, 316.

organisms. Some of the fungi and actinomycetes that can be readily grown on simple culture media and that can lyse the cells of suitable bacteria, can obtain at least part of their food requirements from these lysed cells.

The quantities of these antibiotic substances produced, and their influence on the antagonised organism, depend on external conditions such as food supply, aeration and soil reaction, but the details of these dependencies have not been worked out fully enough to allow any generalisation applicable to the mixed soil population to be made. These antibiotic substances may collect in the subsoil, for A. S. Newman and A. G. Norman[1] found that the microflora of an arable soil below the depth of cultivation responded to additions of fermentable material much more slowly than did those in the surface soil, and this response was not increased by inoculating the subsoil with some surface soil.

Crops may perhaps sometimes suffer from these substances. Thus, R. A. Steinberg[2] has shown that tobacco plants show morphological deformities if grown near some strains of non-pathogenic bacteria in otherwise aseptic conditions, and this was due to soluble organic compounds diffusing from the bacterial cells; and he could reproduce these symptoms by allowing a very low concentration of some organic compounds, such as the amino acid isoleucine, to build up around the roots.[3] Now these symptoms are typical of "frenching" in tobacco, a disease not apparently due either to a nutrient deficiency or to a pathogenic organism. Hence, he suggested that the cause of frenching in the field is due to too high a concentration of diffusible microbial products accumulating in the soil near the tobacco roots.

Bacteria can also be parasitic on soil fungi. Cholodny slides buried in soil repeatedly show portions of fungal mycelia being attacked by bacteria: one end of the mycelium appears free from bacteria, then comes a large concentration of small rods and cocci on what appears to be almost empty mycelium, and behind this the original line of the mycelium can be followed by colonies of bacteria outlining the old wall. The interpretation of this observation is not clear. P. C. O. Jones[4] showed that even if the fungi were growing in the absence of bacteria the main fungal protoplasm appeared to keep in the growing parts of the mycelium, leaving the back parts almost empty, and it may be that the bacteria are simply attacking these nearly empty regions. On the other hand, R. L. Starkey[5] considered that the fungal tissue on which the bacteria were living could not provide enough food for the development of all these bacteria, and assumed they can extract nutrients from the living mycelium before it is killed. Bacteria may,

[1] *Soil Sci.*, 1943, **55**, 377.
[2] *J. Agric. Res.*, 1947, **75**, 199.
[3] *Science*, 1946, **103**, 329; *J. Agric. Res.*, 1947, **75**, 81.
[4] I am indebted to Mr. Jones for this information.
[5] *Soil Sci.*, 1938, **45**, 207.

therefore, play an important role in limiting the amount of fungal mycelium in a soil, though their importance cannot yet be assessed as there are so many organisms in the soil that can feed on fungal mycelium; and, in fact, it seems that the life of any long piece of mycelium in the soil must be fairly short.

These interrelations between the various members of the microflora may be of considerable importance in the control of plant pathogens in the soil, for the growth of some pathogenic fungi can be inhibited by some common soil fungi and bacteria. R. Weindling[1] has claimed that the soil fungus *Trichoderma lignorum* can control the damping-off of citrus seedlings by a *Rhizoctonia*, and A. Lal[2] that it can control *Ophiobolus graminis*, the fungus causing "take-all" in wheat and barley. J. P. Chadiakov[3] has also claimed that bacteria of the genera *Pseudomonas* and *Achromobacter* can control some *Fusaria*, causing a wilt of flax.

The great practical difficulty is to find means of encouraging these desirable fungi or bacteria to multiply, for they can only control the pathogenic organisms effectively if they are sufficiently active in the soil, that is, if they have an adequate food supply. It cannot usually be done by inoculating the desirable organism into the soil, as it will not be able to compete with the indigenous population for food, nor in general will adding an inoculum of a desirable organism already present help, for again the extra numbers of the organism will not usually be able to find enough food to keep them active. However, C. H. Meredith[4] has reported what appears to be an exception to this rule, for he claimed to have reduced the severity of panama disease in bananas, caused by the fungus *Fusarium oxysporum* var. *cubense* by adding to the soil an inoculum of an actinomycete derived from the soil itself which is antagonistic to this fungus.

The only way desirable organisms can have their activity increased is by altering the soil conditions. This can be done in two ways: either by adding organic matter and increasing the activity of the whole saprophytic population, and this will usually increase the activity of organisms that are antagonistic to specialised plant pathogens; or by altering the soil conditions in such a way that the desirable organisms can obtain a larger share of the available food supply. Thus, the fungus causing root rot in cotton, *Phymatotrichum omnivorum*, can be kept in control in irrigated Arizona fields by adding 10 to 15 tons of manure or other decomposable organic matter annually to the soil well before the cotton is planted.[5] Weindling and Fawcett showed that the

[1] *Phytopath.*, 1932, **22**, 837; 1934, **24**, 1153; 1936, **26**, 1068; with H. S. Fawcett, *Hilgardia*, 1936, **10**, 1.
[2] *Ann. Appl. Biol.*, 1939, **26**, 247. [3] *Mikrobiologia*, 1935, **4**, 193. [4] *Phytopath.*, 1946, **36**, 983.
[5] C. J. King, *U.S. Dept. Agric., Circ.* 425, 1937; for corresponding results in Texas, see R. B. Mitchell *et al.*, *J. Agric. Res.*, 1941, **63**, 535.

Rhizoctonia fungus causing damping-off of citrus seedlings could be controlled in the field by *Trichoderma lignorum* if the soil was made sufficiently acid for the *Trichoderma* and similar fungi to multiply at the expense of the majority of the soil population. And the cotton root rot fungus can be attacked by saprophytic fungi in the roots of the cotton plant after harvest if the cotton plant is then cut below the crown; for this injury allows saprophytic fungi to enter the roots rapidly and destroy the root rot fungus in the process of attacking the root cells themselves.[1] Some further methods of controlling fungi attacking plant roots will be described later on p. 217.

The problem is in some ways easier when the pathogenic fungus can only live in plant tissue, and is carried over in the soil in infected tissue, for anything that hastens the decomposition of the plant remains in the soil hastens the killing-out of the fungus. However, although the problem is easy in theory, it is difficult to find suitable methods in practice because the infected plant remains are usually resistant to decomposition. As an example, *Ophiobolus graminis*, the cause of take-all in wheat and barley, is carried in the soil in infected straw, and it is not possible to get all the stubble decomposed between harvest-time in August and the beginning of the next growing season in March. But it may be possible to help the soil organisms in their work of destroying the pathogen if its resistance can be weakened in any way. In the particular case of *Ophiobolus*, S. D. Garrett[2] has shown this can be done by depleting the soil of available nitrogen directly after harvest; for the fungus, which is growing in the nitrogen-poor straw, appears to need some soil nitrogen during this period. Hence, any device which does this, such as under-sowing the corn with Italian rye-grass or trefoil, for young trefoil takes up soil nitrogen in autumn, will weaken the fungus. When the rye-grass or trefoil is ploughed in in the spring, the readily available nitrogen in the green manure is released as nitrate which the young barley crop takes up. As shown on p. 217, the resistance of corn to damage by *Ophiobolus* is increased as the general level of fertility, and of available nitrogen in particular, is increased; and for this reason trefoil is preferable to Italian rye-grass as the under-sown crop.

Interactions between the Soil Microflora and Fauna

The standard example of the relation between the soil's fauna and microflora is that between the protozoa and bacteria, though B. N. Singh's work has shown that other protozoal-like organisms, such as myxobacteria, *Acrasieae*, giant amoeboid organisms and presumably

[1] F. E. Clark, *U.S. Dept. Agric., Tech. Bull.* 1942, 835.
[2] *Ann. Appl. Biol.*, 1944, **31**, 186; 1948, **35**, 435.

myxomycetes all feed on bacteria as well. Bacteria, however, vary in their edibility to these different organisms: some bacteria appear to be readily eaten by them all, some by only a few, and a few appear to be inedible to all the organisms tested—these latter mainly being pigmented bacteria which may secrete strong antibiotics. Thus, out of eighty-seven different bacterial species of various origin tested for edibility by five groups of these organisms, a soil amoeba, a myxamoeba, a giant amoeba and two myxobacteria, twelve were eaten by all five groups, twenty-five were eaten by four, seventeen by three, thirteen by two, thirteen by one group only, and seven were not eaten by any.[1] Thus, the great majority of soil bacteria can be eaten by at least one group of these bacterial feeders known to be present in the soil.

The soil fauna can affect the microflora in several ways: the larger saprophytic soil animals, by being motile, distribute both the decaying organic matter and some of the microbial population throughout the soil layer in which they are working; for they will be ingesting food at one place, mixing it with bacteria in their gut, and excreting it at another. In fact, this process of comminuting and distributing dead plant litter throughout the surface layers of the soil is the predominant action of the larger soil invertebrates on the microbial population.

Animals feeding on decaying organic matter, and particularly those that ingest soil at the same time, also affect the composition of the microbial population, for these animals will always be taking into their gut the micro-organisms attached to the plant residues or soil ingested, and be subjecting them to the action of their digestive juices, though whether they can in fact affect the composition of the microbial population is not known. It is possible that earthworms can depress fungal development in the soil by feeding on fungal mycelia, for it is an interesting fact, of unproven generality, that fungal mycelia only seem to develop abundantly in those soils of the temperate regions where earthworms are scarce, though more experimental work is needed to establish the validity and interpretation of this generalisation.

There appears to be another interaction of importance, this time between the soil invertebrates and the protozoa, for some of the saprophytic invertebrates carry a protozoal population in their gut to help digest some of the more resistant plant products, such as cellulose, which the animal appears to feed on. Thus, the digestive tracts or organs of some soil invertebrates constitute an important environment of the soil protozoa—an environment of presumably great activity.[2]

[1] F. J. Anscombe and B. N. Singh, *Nature*, 1948, **161**, 140.
[2] For an account of this, see E. A. Steinhaus, *Insect Microbiology*, Ithaca, N.Y., 1946.

The Effect of Soil Conditions on the Soil Microflora

The composition of the soil population depends on soil conditions, particularly on the sources of energy available and on the air and water régime, but it does not show striking geographical changes. The same characteristic groups of bacteria, fungi, algae and protozoa are much the same in arctic, temperate and tropical soils, the differences between zones being far less marked than are those for the distribution of higher plants and animals. The reasons for this constancy of the soil population are to be sought, partly in the nature of the organisms themselves, partly in the soil as a habitat. It is possible, and indeed probable, that micro-organisms are less susceptible to environmental conditions than are the larger forms; also the biological conditions at a depth of from 2 to 7 or 8 inches below the soil surface are more constant than on the surface itself; the temperature is more even (p. 332), and the atmosphere is almost always humid and nearly saturated: there are no marked differences in degree of humidity such as affect profoundly the distribution of plants.

The numbers of the bacteria in particular and their associated protozoa are constantly varying. The causes of these variations cannot be completely analysed, for in a mixed interrelated population such as occurs in the soil, a change in numbers of a single species will automatically cause the changes in the numbers of other species. These fluctuations make it difficult to trace the effect of external conditions on the behaviour of any group of soil micro-organisms, and this difficulty can only be overcome by devising long series of experiments using proper statistical control to minimise their importance.

Nearly all the work on the effect of soil factors on the numbers of the bacteria, actinomycetes and fungi has been done using the plating technique, so that many of the results given in the next sections are uncertain. It is very desirable that they be checked, using the more direct methods of estimating bacterial numbers and the amount of actinomycete and fungal hyphae present.

SOIL MOISTURE AND SOIL TEMPERATURE

These two factors have quite different influences on two distinct aspects of the soil microflora: their numbers and their activity. The bacterial numbers in a soil appear to increase with increasing moisture content, a result found by every investigator, though it has only been established for numbers based on the plate count. H. L. Jensen,[1] working with a pasture soil in New South Wales, found the numbers of actinomycetes were almost independent of the moisture content, so that the ratio of actinomycetes to bacteria increased as the moisture

[1] *Proc. Linn. Soc., N.S.W.*, 1934, **59**, 101.

content decreased, but the number of fungi increased with moisture content; whilst W. G. E. Eggleton,[1] using an English pasture soil, found the actinomycetes increased somewhat with moisture content, though not as much as the bacteria, but the number of fungi was independent of the moisture content. It is, however, probable that these fungal results reflect more the limitations of the technique used than their field behaviour, for H. J. Conn,[2] using the Cholodny slide technique and soils incubated in the laboratory, found that fungal mycelia were prominent in the drier and absent in the wetter conditions—a result in accord with our general knowledge that many soil fungi thrive in fairly dry conditions but demand good aeration for active growth.

The effect of the usual variations of soil temperature on the number of micro-organisms is still undecided. The careful work of Jensen and of Eggleton on pasture soils, and N. James and M. L. Sutherland[3] on a fallow soil in Winnipeg all failed to show any effect of temperature on the numbers of the soil bacteria if the associated moisture effects were eliminated. Eggleton found the number of actinomycetes increased somewhat with temperature, a result not found by Jensen, and neither found any effect of temperature on the number of fungi. On the other hand, D. W. Cutler and L. M. Crump,[4] using a fallow soil at Rothamsted, found the numbers of bacteria tended to decrease with increasing temperature, and D. Fehér and M. Franck,[5] using Hungarian pasture and forest soils, found they increased.

The effect of the season of the year on the number of bacteria, as determined by the plating method, appears to be small for soils that are either fallowed or are under forest or permanent pasture: the linear regression with moisture content accounts for about half the total variability (variance) of the bacterial numbers in Jensen's, Eggleton's, and James and Sutherland's[6] experiments. But the effect of an annual crop on bacterial numbers is considerable. James and Sutherland found the number of bacteria in the wheat soil, reduced to a standard moisture content, was the same as the fallow soil at the end of May, but was nearly double that at the end of September. The effect of season on actinomycetes and fungi has not been so fully investigated. Under pasture conditions Jensen found less of the variability could be removed by the temperature and moisture regression, though Eggleton found about as much of the actinomycete as the bacterial variability could be so accounted for; whilst J. Singh[7] working on the permanent wheat and mangold plots at Rothamsted, found no apparent seasonal effect on the numbers of fungi or actinomycetes.

[1] *Soil Sci.*, 1938, **46**, 351. [2] *New York State Agric. Expt. Sta., Tech. Bull.* 204, 1932.
[3] *Canad. J. Res.*, 1940, **18** C, 435. [4] *Problems in Soil Microbiology*, p. 14.
[5] *Arch. Mikrobiol.*, 1933, **4**, 447; 1937, **8**, 249; 1938, **9**, 193.
[6] *Canad. J. Res.*, 1943, **21** C, 119. [7] *Ann. Appl. Biol.*, 1937, **24**, 154.

Variations of moisture content and temperature cause many changes in the activity of the micro-organisms that are not connected with their number. The activity of all aerobic organisms in a soil increases with increasing moisture content up to a maximum and then begins to decrease, due to the reduction in oxygen supply caused by the excess water (see Fig. 17[1]), and the activity of all organisms increases with

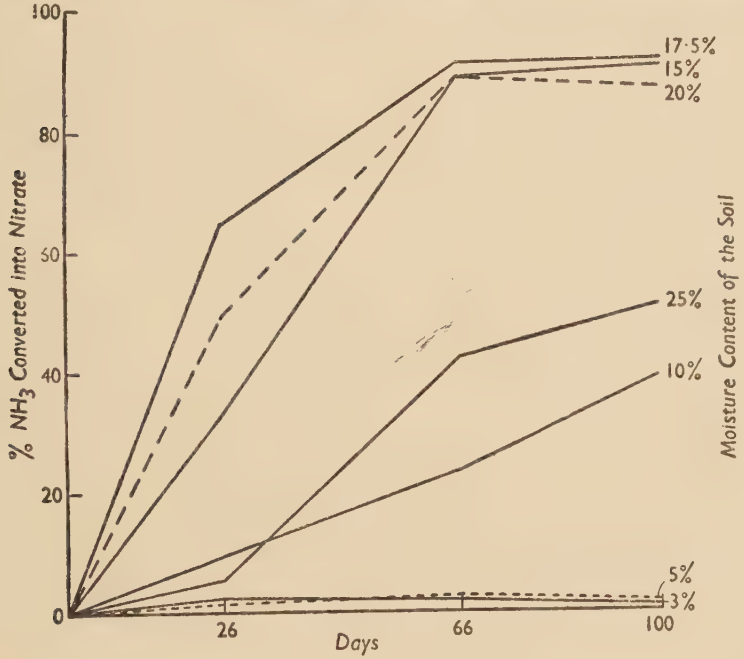


Fig. 17. Effect of moisture content of the soil on the proportion of ammonia, added as ammonium sulphate, oxidised to nitrate.

increasing temperature up to a maximum and then decreases when the higher temperatures are injuring the organism. Thus, the net effect of these factors on the activity of a group of organisms in the soil is the product of the number of organisms present and their individual activities; and the maximum activity may, and for temperature dependence usually does, occur when the numbers are falling. The relation between temperature and activity can, however, become very complex when two or more organisms are living together. Thus, E. H. Richards[2] showed that the rate of nitrogen fixation by *Azotobacter*, living in the presence of starch-decomposing organisms of the Aerogenes group and feeding on the by-products of the decomposition, had two optimum temperatures, the one at the higher temperature corresponding to low

[1] A. E. Traaen, *Zbl. Bakt.* II, 1916, **45**, 119.

[2] *J. Agric. Sci.*, 1939, **29**, 302.

numbers but high activity due both to the temperature directly and also to the more abundant food supply produced at the higher temperature by the Aerogenes bacteria.

Jensen[1] investigated the effect of temperature on the relation between the CO_2 evolution of a soil and the number of bacteria it contained, and showed that as the temperature rose the CO_2 evolved per 1,000 million bacteria, as determined by the direct cell count, increased from about 16 per cent of their dry weight per day at 15° C. to 30 per cent at 28° C. and to 50 per cent at 37° C., whilst if plate counts were used as the basis there was no clearly marked temperature dependence, and for some soils the CO_2 evolution per day would be over sixty times the dry weight of the organism, which would correspond to higher rates than observed for young cultures of active bacteria growing under optimal conditions. He considered the fungi were inactive under these conditions.

When decomposable organic matter was added to the soil, Jensen found that the fungi, as measured by the abundance of mycelia on the Cholodny slides, came into prominence, and the density of mycelium was correlated with the CO_2 production; in fact, the multiple correlation of this and the total cell count for bacteria with CO_2 production was about 0·8. At low temperatures, 4° to 7° C., the importance of the fungi was small compared with the bacteria, at 14° to 16° C. it was about equal to that of the bacteria, at 28° C. it was considerably larger, and at 37° C. it was equal or less; but in all these cases this was only true for the first week of decomposition, after that the fungal activity fell off rapidly compared with the bacterial.

THE EFFECT OF SOIL REACTION

The effect of soil reaction can be very marked under conditions of extreme acidity, though, as will be discussed later in connection with plants (see p. 473), the effect of the hydrogen-ion concentration may be less important than associated effects such as the lack of calcium or phosphates, or the presence of soluble aluminium and manganese compounds.

One of the most important effects of great acidity is the absence of burrowing animals, such as the earthworms, which mix the surface litter with the soil. Dead and partially decomposed plant material accumulates on the surface as a mat, and the population below the soil surface lives under conditions of very small annual additions of nutrients. It is possible that fungi may be transferring nutrients from the mat to the soil by sending their mycelia into each region, but the importance of this transfer has not been established.

[1] *Proc. Linn. Soc., N.S.W.*, 1936, **61**, 27.

Acid soils probably carry a larger fungal but a smaller bacterial flora than neutral soils. Acid mor soils, whose *p*H usually lie below 4, are typically characterised by a profuse development of fungal mycelia, which are far less prominent on less acid mull soils (see p. 515). But if the acidity is not extreme, the evidence is not extensive enough to admit of any rigid generalisations. Thus the bacterial population on Rothamsted pasture soils is not dependent on *p*H in the range 3·8–5·6 if bacterial numbers are determined by Thornton and Gray's total cell count, though they are depressed at the lower *p*H if determined by the plate count. Jensen's work, just quoted, suggests that the total cell count gives a more accurate estimate of bacterial numbers, with the consequence that at the present time it is best to assume that the total bacterial population is not very dependent on soil reaction.

The type of bacteria present in the soil depends on the soil reaction. Nitrifiers, i.e. bacteria oxidising ammonia to nitrites and nitrates, are relatively inactive in acid soils, though the *p*H by itself cannot be the sole cause of this, as it also depends on the vegetation. Thus, C. Olsen[1] found that nitrates were produced down to *p*H 3·8 in Danish pasture soils, but only to *p*H 4·5 in forest soils, whilst H. L. Richardson[2] found very little nitrate produced below *p*H 6 in a Rothamsted pasture. Again, the common species of the aerobic nitrogen-fixing Azotobacter are usually absent in soils with *p*H below 5·7.

Very little definite information appears to be available on the effect of alkaline reactions on the type of micro-organisms present in the soil, though there is some evidence (p. 291) that nitrifying organisms may be limited by phosphate starvation under very alkaline conditions.

Partial Sterilisation of the Soil

The soil population can be greatly simplified, and undesirable groups of pathogens can be eliminated from the soil by partial sterilisation. This consists either in heating the soil with steam or in adding to it sterilising solutions such as toluene and carbon disulphide, and this treatment increases the fertility of the soil markedly for a time.

Relatively mild treatments, such as drying the soil, heating to 45° C., treatment with poisons which are not too strong,[3] cause a fall in numbers of bacteria, but when the conditions are again made suitable, the numbers rise considerably. They do not remain high, but sooner or later fall to the normal range of values.

More drastic treatment, such as heating the soil to 50° C. (at which temperature most of the trophic forms are killed), or treatment with

[1] *C.R. Lab. Carlsberg*, 1923, **15**, 1. [2] *J. Agric. Sci.*, 1938, **28**, 73.

[3] The effect of poisons was first observed by Oberlin in Alsace (*Bodenmüdigkeit und Schwefelkolhlenstoff*, Mainz, 1894).

certain stronger poisons, also causes a fall and subsequent rise in bacterial numbers when favourable conditions are restored, but the high numbers are maintained much longer. The phenomena are not confined to soil, but are shown also by other complex microbial associations, such as sewage beds.[1] According to S. A. Waksman and R. L. Starkey,[2] the fungi in soil are first much depressed, but increase greatly in numbers soon after the conditions again become favourable. The actinomycetes are also at first depressed, though nothing like as much as the fungi: they do not recover as quickly as the bacteria, though they multiply rapidly if cellulose or other energy material be added. E. J. Russell and H. B. Hutchinson showed that the numbers of bacteria in partially sterilised soils, unlike those in normal soils, reacted in accordance with expectation towards changes in temperature and water content.

As a general explanation E. J. Russell suggested that the treatment, by curtailing or eliminating (according to its severity) one or more of the groups of the soil population, leaves the others more free from competition, and, therefore, able to increase to higher numbers than before, and also to react normally to changes in external conditions. This view was put in more concrete form in conjunction with H. B. Hutchinson,[3] and evidence was adduced that bacteria, at that time regarded as the only important living micro-organisms in the soil, were not so in fact, but that other organisms were normally present keeping down their numbers. It was shown that these organisms were probably protozoa, a view that Cutler subsequently substantiated.[4]

The organisms surviving partial sterilisation produce more ammonia and nitrate than did the original population, so that soils treated by methods calculated to injure trophic life gain in fertility, an apparently paradoxical result in view of the importance of trophic life to soil fertility (Table 43).

Partial sterilisation of soil has, however, under some conditions not yet defined, increased the amount of ammonia and nitrite in the soil,[5] suppressing the oxidation of nitrite to nitrate; and under these conditions plants will rapidly die from nitrite poisoning. Further it may also increase the amount of available manganese in the soil sufficiently to cause plants growing on it to suffer from manganese poisoning,[6] and this

[1] The disinfection of sand filters leads to increases in the numbers of bacteria. This was observed in the typhoid epidemic at Lincoln in 1904, and also in the experimental sewage filter at Guildford in 1907: A. C. Houston and G. McGowan, *5th Rept., Sewage Commission*, Appendix IV, Cd. 4282, 1910, p. 111.

[2] *Soil Sci.*, 1923, **16**, 137, 246, 343.

[3] *J. Agric. Sci.*, 1909, **3**, 111; 1913, **5**, 152.

[4] For a study of the effect of naphthalene on the bacterial and protozoan populations of greenhouse soils, see S. E. Jacobs, *Ann. Appl. Biol.*, 1931, **18**, 98.

[5] For an example, see S. B. Mecca, *Flor. Exch.*, 1947, **108**, Nos. 16, 17.

[6] C. K. Fujimoto and G. D. Sherman, *J. Amer. Soc. Agron.*, 1948, **40**, 527; F. H. Dalton and C. Hurwitz, *Soil Sci.*, 1948, **66**, 233.

TABLE 43

Changes produced in Soil by Partial Sterilisation[1]

Weight and composition of crops grown on partially sterilised soils

	Dry Weight of crop	Percentage composition of dry matter			Weight of nutrients taken by the plant from soil, gm.		
	gm.	N	P	K	N	P	K
Buckwheat:							
Untreated soil . .	18·14	2·75	0·815	4·68	0·499	0·174	0·849
Soil treated with carbon disulphide .	23·27	3·15	1·020	4·97	0·733	0·238	1·158
Mustard:							
Untreated soil . .	15·88	2·30	0·436	3·50	0·367	0·069	0·556
Heated soil . .	24·33	4·43	0·908	4·19	1·077	0·221	1·019

Ammonia and Nitrate Accumulating in a Soil kept Twenty-three Days at about 15° C. in a Moist Condition[2]

Parts per million of dry soil

	Nitrogen present as ammonia		Nitrogen present as nitrates		Total nitrogen present as ammonia and nitrate		
	At beginning	After 23 days	At beginning	After 23 days	At beginning	After 23 days	Gain in 23 days
Untreated soil . .	1·8	1·7	12	16	13·8	17·7	3·9
Soil heated 2 hours to 98° C. . . .	6·5	43·8	13	12	19·5	55·8	36·3
Soil treated with toluene, which was then evaporated . .	5·0	27·8	12	12	17·0	39·8	22·8
Soil treated with toluene, which was not removed . . .	7·2	14·5	11	10	18·2	24·5	6·3

may explain some of Russell's results that plants were sometimes harmed when growing on soils sterilised at too high a temperature.

The fact has long been known to cultivators of the soil. Heating the soil has been practised from time immemorial in India; the process is called "rab", and is mentioned in the Vedas;[3] the burning of stubble was known by the Romans to increase the fertility of the soil, and various possible explanations were shrewdly put forward by Virgil.[4]

[1] F. V. Darbishire and E. J. Russell, *J. Agric. Sci.*, 1907, **2**, 305.
[2] E. J. Russell and H. B. Hutchinson, *J. Agric. Sci.*, 1909, **3**, 111.
[3] "Like to a tender plant whose roots are fed,
On soil o'er which devouring flames have spread."
Stories of the Buddha's Former Births. Trans. H. L. Francis.
[4] *Georgics*, Bk. I, 84–93.

Exposure of the soil to the baking heat of the sun is an ancient practice still common in India[1] and in Egypt, where it is known as *sheraqi*, and has been studied by J. A. Prescott[2] and shown to be due partly to microbiological, and partly to physical, causes. A. N. Lebediantzev[3] considers that this repeated drying and heating of the soil plays no small part in maintaining its fertility in hot countries. The effects on the plant are in all cases described as resembling those of nitrogenous manure.

This increased production of ammonia and nitrate is not a necessary consequence of the higher numbers of organisms; on the contrary, higher numbers, e.g. those induced by adding non-nitrogenous organic matter to the soil, might depress the ammonia and nitrate content (p. 235) by taking up these substances for their own nutrition. The increased production of ammonia and nitrate is a distinct phenomenon, and several explanations have been put forward to account for it.

L. Hiltner and K. Störmer,[4] who were the first to associate the beneficial effects of partial sterilisation with bacteria,[5] considered that the new bacterial flora set up after the treatment was more potent in decomposing protein than the old one. This view was shown to be inaccurate by Russell and Hutchinson, who replaced the old flora by inoculating untreated soil into partially sterilised soil, and showed that the bacterial numbers rose even higher, and produced even more ammonia and nitrate, than did the new flora by itself.

The idea was modified by Waksman and Starkey, who suggested that in normal soil much of the decomposition of the protein is effected by fungi, which assimilate a good deal of the carbon and a corresponding amount of nitrogen; after partial sterilisation, however, the fungi are for a time suppressed and the decomposition passes to the bacteria which assimilate much less of the carbon and nitrogen and, therefore, produce a larger amount of ammonia.

Russell and Hutchinson connected the increased ammonia production with the increased numbers of bacteria, supposing that the new bacterial flora was not widely different from the old, and might therefore be expected to behave like the old, except that, being more numerous, it would accomplish more decomposition. The close relationship between bacterial numbers and ammonia (or nitrate) production in their experiments supported this view. Störmer suggested that the additional ammonia and nitrate came from the decomposition by bacteria of the organisms killed by the partial sterilisation process.

[1] A. and G. L. C. Howard, *Nature*, 1910, **82**, 456.
[2] *J. Agric. Sci.*, 1919, **9**, 216; 1920, **10**, 177.
[3] *Soil Sci.*, 1924, **18**, 419.
[4] *Arb. Biol. Abt. Land. u. Forstw. Kais. Gesundh. Amt.*, 1903, **3**, 445.
[5] The earlier investigator, A. Koch, had attributed the increased productiveness to a direct stimulation of the plant.

The amounts formed, however, are much larger than correspond with our present estimates of the soil population; in the Rothamsted soil they are of the order of 20 to 50 parts of nitrogen per million of soil, while the whole protozoan and bacterial population represents only 4 parts: estimates of the nitrogen in soil fungi are, however, only rough.

There is thus still no satisfactory explanation of why partial sterilisation, either by steaming or by the use of antiseptics, increases the rate of production of ammonium or nitrate nitrogen.[1]

These problems of partial sterilisation are gaining in practical importance at the present time with the introduction of relatively cheap sterilising agents, such as calcium chloracetate and the chlorinated hydrocarbons, e.g. D-D, which is a mixture of 1,3-dichloropropene and 1,2-dichloropropane. These chemicals have been found to control root-attacking nematodes in the laboratory and to give very considerable increases of crop when added at the rate of several hundred pounds per acre to eelworm-infested land. But it appears that at least under some conditions the chemicals are not affecting the nematodes in the field,[2] so the crop is not responding to the decreased attack of the nematodes so much as to the general increased fertility brought about by the partial sterilising effect these chemicals have on the soil.

[1] For a recent review, see *Soils and Fert.*, 1948, **11**, 357.

[2] See, for example, D. G. O'Brien *et al.*, *J. Helminth.*, 1939, **17**, 41; E. E. Edwards, ibid., 51; D. Price Jones, *Ann. Appl. Biol.*, 1947, **34**, 240.

CHAPTER XIII

THE ASSOCIATION BETWEEN PLANTS AND MICRO-ORGANISMS

The Rhizosphere Population

The influence of the plant roots on the soil population in their neighbourhood is considerable, for plant roots, rootlets and root hairs may carry large concentrations of micro-organisms on their surface.[1] Not all the rootlets or root hairs carry these concentrations, and those that carry them are not necessarily uniformly covered with them. The interfacial volume between the plant rootlets and the bulk of the soil, in which this population lives, is often called the Rhizosphere;[2] but this volume has no exact bounds, for some of the rhizosphere population may penetrate the outer surface of the rootlet and some will extend into the neighbouring soil.

The early work on the relations between the microbial population around the plant roots and that in the bulk of the soil was confined to showing that more bacteria could be plated from soil in the immediate neighbourhood of plant roots than from soil well away from the roots. The Rossi-Cholodny slide technique can be made to give a clear picture[3] of the micro-organisms around rootlets, but improved techniques employing either direct observation of the living rootlet *in situ* or improved methods of fixing, staining, cleaning and mounting rootlets shows that the Rossi-Cholodny pictures give only a partial picture.

The picture obtained from viewing living plant rootlets in the soil[4] is that there are obvious concentrations of micro-organisms around the rootlets, but that there appear to be few in the body of the soil itself. Large colonies of small bacteria occur in clumps, or even sheaths around the rootlets, and large numbers of motile bacteria may be swimming in the thin water films around them, and actinomycete and fungal hyphae of various types can be seen on the surface or even penetrating their epidermal cells. This concentration of the microflora around the plant roots encourages the development of predatory protozoa and nematodes which feed on this population.[5]

[1] For a recent review of this subject, see H. Katznelson, A. G. Lochhead and M. I. Timonin, *Bot. Rev.*, 1948, **14**, 543.

[2] L. Hiltner, *Arb. deut. landw. Ges.*, 1904, **98**, 59, first used this word.

[3] See N. Hulpoi, *Arch. Mikrobiol.*, 1936, **7**, 579; R. L. Starkey, *Soil Sci.*, 1938, **45**, 207; and M. I. Timonin, *Canad. J. Res.*, 1940, **18**C, 444, for photographs of the kind of information these slides give.

[4] This description is taken from M. B. Linford, *Soil Sci.*, 1942, **53**, 93.

[5] See also H. Katznelson, *Soil Sci.*, 1946, **62**, 343.

The size of this population has mainly been investigated using the plating technique[1] and since this may give numbers for the bacteria in the soil a hundredfold smaller than is obtained by the total cell count, it is possible that the rhizosphere effect might be in part a reflection of this difference between techniques, for as will be shown later, the rhizosphere population tends to grow rather easier on relatively simple media and to have a higher activity, hence to grow more quickly on the relatively concentrated nutrient media used in the usual plating technique.

The significance of this population for plant growth is not fully understood. It probably helps the plant to extract phosphate[2] and possibly other nutrients from difficultly available compounds, though whether this is entirely due to the higher CO_2 concentration the microorganisms produce around the root hairs has not been established. The population, on the other hand, must obviously derive some benefit from the plant; presumably a proportion at least must draw their energy supply from the plant, partly directly from the living and partly indirectly from the dead or dying tissues, but no estimates are yet available of the proportion of the carbohydrate fixed by the plant that is used by this population.

In spite of these limitations there is little doubt about the correctness of the general conclusions reached by this older work, namely, that the soil in the immediate neighbourhood of the plant roots carries a larger, or possibly only a more active, population than that away from the roots. It is consistent with all qualitative observations so far made, and also with the evidence from the rate of CO_2 production of the soil, which is greater near the root than a little way away from it. In fact R. L. Starkey[3] found that there was a rough correlation between the rate of evolution of CO_2 by roots and the number of bacteria in the rhizosphere, suggesting that the microbial population on the root makes an appreciable contribution to the rate of CO_2 evolution in the immediate neighbourhood of the root surface.

It is still more difficult to assess the relative importance of the rhizosphere population compared with the general soil population when expressed as the proportion of the bacteria present per acre of soil in these two populations. N. A. Krassilnikov[4] has made a rough estimate of uncertain validity and concludes that there is probably about twice the weight of bacteria in the lucerne rhizosphere as in the body of the soil, namely, about 2 tons and 1 ton live weight per acre respectively, whilst the bacterial rhizosphere of a wheat crop growing in relatively

[1] R. L. Starkey's work (*Soil Sci.*, 1929, **27**, 319, 355, 433; 1931, **32**, 367) is a good illustration of the type of results obtained by these methods.

[2] F. C. Gerretsen, *Plant and Soil*, 1948, **1**, 51.

[3] *Soil Sci.*, 1931, **32**, 367.

[4] *Mikrobiologia*, 1944, **13**, 144.

infertile soil probably only weighs about 5 lb. per acre and, in consequence, is negligible compared with the rest of the population.

The size of the bacterial rhizosphere population depends on the plant and on its stage of development, but is not very dependent on the fertility of the soil;[1] though since the less fertile soil will often have a lower population, the difference in numbers between the rhizosphere and the soil populations may be higher in the less fertile than the more fertile soils.[2] For a given plant, the population is most numerous when it is making its most vigorous growth.[3] The effect of the type of plant has not been investigated critically, but under comparable conditions clovers, sweet clovers and lucerne probably carry a considerably higher population than arable crops, including beans.

The plant roots will sometimes supply a part of the population with simple amino acids and with growth factors such as aneurin and biotin. A. I. Virtanen[4] showed that pea roots might sometimes excrete the amino acids, aspartic acid and β-alanine; P. M. West[5] showed that the roots of flax and tobacco could excrete growth factors such as aneurin and biotin; and H. Lundegårdh and G. Stenlid[6] found that wheat roots could excrete nucleotides and flavanones. Further, Lochhead and other Canadian workers have shown that the rhizosphere bacterial population differs from that in the soil as a whole by having a lower proportion of bacteria that require complex growth substances, such as yeast and soil extract, and a higher proportion with very simple requirements, although those on some crops, e.g. flax, require some simple growth substances and those on others, e.g. red clover, require amino acids as well.[7] This presumably indicates that these crops excrete such substances, lending support to the hypothesis that leguminous crops excrete amino acids even when their root system is too young for the sloughing off of rootlets or nodules to be expected.

The rhizosphere bacterial population differs from that of the soil in its morphological as well as its nutritional composition. R. L. Starkey[8] showed that a large proportion of the rhizosphere bacteria belong to the *Radiobacter*, or in Conn's terminology (see p. 151) the *Agrobacter* group which includes the nodule bacteria for leguminous plants. These are Gram-negative, non-spore formers, which may include some fluorescent types as well, but spore-formers are rare. Lochhead[9]

[1] F. E. Clark and C. Thom, *Trans. 3rd Comm. Int. Soc. Soil Sci.*, New Brunswick, 1939, A, 94.
[2] P. M. West and A. G. Lochhead, *Canad. J. Res.*, 1940, **18** C, 129.
[3] H. Katznelson, *Soil Sci.*, 1946, **62**, 343.
[4] *Cattle Fodder and Human Nutrition*, Cambridge, 1938.
[5] *Nature*, 1939, **144**, 1050.
[6] *Arch. Bot.*, 1944, **31** A, No. 10.
[7] R. H. Wallace and A. G. Lochhead, *Soil Sci.*, 1949, **67**, 63. For earlier work, see A. G. Lochhead, *Canad. J. Res.*, 1940, **18** C, 129; A. A. Hildebrand and P. M. West, ibid., 1941, **19** C, 183; H. Katznelson and L. T. Richardson, ibid., 1943, **21** C, 249; A. G. Lochhead and R. H. Thexton, ibid., 1947, **25** C, 20.
[8] *Soil Sci.*, 1929, **27**, 355.
[9] *Canad. J. Res.*, 1940, **18** C, 42.

showed that the population has a higher activity, e.g. it contains a higher proportion of forms that are coloured and are motile and that will grow more actively in nutrient media than the soil population as a whole.

Little additional knowledge about the occurrence of specific groups of bacteria in the rhizosphere is available. H. Katznelson[1] found that the population around mangold roots appeared to have a higher proportion of cellulose decomposers and anaerobes, such as *Clostridia*, than the soil as a whole, but that *Azotobacter* showed no concentration in the rhizosphere, a result in accord with much other work.[2] M. I. Timonin[3] found that manganese oxidising bacteria could be so prevalent in the rhizosphere of some varieties of oats that the oats could not take up enough manganese, so suffered from grey speck disease, whilst other varieties of oats, growing under the same conditions, had a smaller population of these bacteria and could take up enough manganese. The numbers of manganese oxidisers in the rhizosphere could be increased and in consequence the severity of the grey speck symptoms, by applying a straw mulch to the soil; and the numbers and the grey speck symptoms could be decreased by adding partial sterilising agents such as chloropicrin, formaldehyde and even calcium cyanamide to the soil.

Association of Fungi with Plant Roots

Plant roots, even from apparently healthy plants, carry a considerable fungal population in and around their roots in addition to the bacterial. The fungus enters the epidermal cells of the roots, and is usually restricted to them. These fungi may, but do not always, kill the cells they invade, and the species range from those that are definitely pathogens to those that may benefit a healthy plant. P. M. Simmonds and R. J. Ledingham[4] in Canada studied the fungal flora on and in the surface of the roots of apparently healthy wheat plants, by digging up the roots, cutting off short lengths, washing them well and putting them in potato agar, a medium that is favourable to the growth of most fungi. In this way they showed that half the infections and a third of the species recognised were due to recognised pathogens, and these infections were much more common in the roots taken from the first foot of soil than from greater depths. They made the further interesting observations that none of the fungi that were only found below the first foot was a pathogen and that the phycomycete mycorrhizal fungus (see p. 226), which did not seem to harm the root in any

[1] *Soil Sci.*, 1946, **62**, 343. [2] See, for example, F. E. Clark, *Soil Sci.*, 1948, **65**, 193.
[3] *Proc. Soil Sci. Soc. Amer.*, 1947, **11**, 284. For earlier work on this, see F. C. Gerretsen, *Ann. Bot.*, 1937, **1**, 207. For a possible example of zinc deficiency in orchards caused by rhizosphere bacteria, see D. R. Hoagland *et al.*, *Proc. Amer. Soc. Hort. Sci.*, 1938, **34**, 210, and P. A. Ark, ibid., 216. [4] *Sci. Agric.*, 1937, **18**, 49.

way, was much more prevalent in the deeper than in the shallower roots. M. D. Glynne,[1] working with wheat roots taken from the permanent wheat field at Rothamsted, reached the same general conclusions, and further showed that the frequency of infection increased during the growing season, reaching a maximum in June—a result comparable with Katznelson's for bacteria around mangold roots.

Not only the species of plant, but also the actual variety can affect the rhizosphere population, particularly if two varieties are chosen, one of which is relatively susceptible and the other relatively immune to typical fungal root infections. This dependence has been studied in Canada with reference to the difference in population around the roots of flax varieties immune and susceptible to wilt (*Fusarium lini*) and tobacco varieties to black root rot (*Thielaviopsis basicola*).[2] The varieties susceptible to these diseases, even when healthy, carry a larger and a more typical rhizosphere population than the immune. In the case of flax[3] this seems to be due to the immune variety excreting larger quantities of HCN from its roots than the susceptible, which is derived from the decomposition of the larger quantity of the glucoside linamarin which it contains in its roots. This increased HCN concentration depresses some members of the rhizosphere population, particularly the weakly pathogenic soil fungi, e.g. *Fusarium*, *Helminthosporium* and *Verticillium*, without affecting the non-pathogens such as *Trichoderma*, *Mucor* and *Penicillium*.

Problems of great practical importance arise in the attempt to limit the density of pathogenic fungi in the rhizosphere of the plant root, because if soil conditions could be so adjusted that they could not flourish there, it would offer a way of controlling soil-borne fungal diseases in the field.[4] Obviously, one way of doing this is to encourage the general soil population to decompose the pathogenic fungal tissue when in the soil, and the principles of doing this by increasing the general activity of the population have been described on p. 200. Another way is to use a good rotation of crops so the pathogens of each crop used are never able to build up in numbers. And this principle applies to soil-inhabiting fungi that are only weak pathogens. Thus, J. Singh[5] found that species of *Fusarium*, which are very characteristic decomposers of wheat straw and also weak parasites of wheat roots,[6]

[1] *Trans. Brit. Mycol. Soc.*, 1939, **23**, 210.

[2] A. G. Lochhead, *Canad. J. Res.*, 1940, **18** C, 42; with P. M. West, ibid., 1941, **19** C, 183, 199; M. I. Timonin, ibid., 1940, **18** C, 307, 444.

[3] M. I. Timonin, *Soil Sci.*, 1941, **52**, 395.

[4] For a recent discussion of these problems, see S. D. Garrett, *Root Disease Fungi*, Waltham, Mass., 1944.

[5] *Ann. Appl. Biol.*, 1937, **24**, 154.

[6] T. S. Sadasivan, *Ann. Appl. Biol.*, 1939, **26**, 497; A. G. Walker, ibid., 1941, **28**, 333.

were prominent members of the fungal flora of the continuous wheat field at Rothamsted, but they were much less prominent on the continuous mangold field whose crop residues do not encourage them.

The fungal population around the root can be altered in two ways: one is by altering the plant so the fungus cannot attack it or cannot extract much food from it, and the other is by altering the microbiological conditions in the soil.

Many plants have their resistance to fungal infection increased, or suffer less damage from the infection once it has occurred, if growing in conditions of high fertility. A generous but wise use of fertilisers is, in fact, one of the best ways of reducing damage by many of the fungi attacking plant roots. Thus, in England the damage due to take-all and eye-spot of cereals, due to the fungi *Ophiobolus graminis*[1] and *Cercosporella herpotrichoides*[2] respectively, can be reduced by proper manuring, particularly with nitrogen, although in Australia where available phosphate limits plant growth, dressings of superphosphate reduce the severity of take-all very considerably. There is, in fact, no truth in the generalisation, which has often been made, that the use of fertilisers and particularly nitrogen fertilisers, necessarily increases the susceptibility of the crop to fungus diseases; for in many cases they have the opposite effect by increasing the resistance of the plant to root fungus diseases. This result must, however, be interpreted with caution. The manuring does not so much increase the resistance of the crop to infection as reduce the damage done by the fungus, through increasing the power of the crop to make new roots or new tillers to replace these affected by the fungi.

The plant can be modified so that its resistance to invasion by root fungi is increased in other ways besides increasing its general vigour. F. M. Eaton and N. E. Rigler[3] showed that the *Phymatotrichum* fungus causing root rot of cotton enters the root easier the lower the level of carbohydrate in the bark, hence anything increasing this carbohydrate content increases the root's resistance to root rot. Unfortunately, the productive strains of cotton tend to send all their carbohydrates into the boll, so have low concentrations in the root bark. The effect of modifying the microbiological conditions in the soil on the ease with which soil-inhabiting fungi attack plant roots is shown by an observation of A. A. Hildebrand and P. M. West.[4] They were studying root rots of strawberry and tobacco caused apparently by the roots being attacked by a number of common soil fungi, none of which appeared to be primarily responsible for the initial attack in strawberry, though

[1] S. D. Garrett, *Ann. Appl. Biol.*, 1941, **28**, 14.
[2] M. D. Glynne *et al.*, *Ann. Appl. Biol.*, 1945, **32**, 297.
[3] *J. Agric. Res.*, 1946, **72**, 137.
[4] *Canad. J. Res.*, 1941, **19** C, 183, 199.

Thielaviopsis basicola may have been the primary cause in tobacco. They found that this trouble could be considerably reduced if soybean tops were dug into the soil, but not if red clover tops were.[1] Decomposing soybean tops appeared to reduce the number of bacteria in the rhizosphere and to increase the proportion of bacteria there which need simple growth promoting substances or amino acids, i.e. the typical group of rhizosphere bacteria at the expense of bacteria that do not need either. Further, it reduced the number of potentially pathogenic fungi on the strawberry roots. Farmyard manure or decomposing red clover tops had none of these effects. They also found that adding glucose or acetic acid to the soil was as effective in controlling root rot, and had the same qualitative effects on the bacteria and fungi of the rhizosphere as decomposing soybean tops; and H. Katznelson and F. E. Chase[2] found that other carbohydrates had the same effect on the bacterial population as soybean tops and that strawberry leaves and tops had the same effect as clover, but they did not test if these had the same effect on the prevalence of the rots.

This work opens up the possibility of using crop rotations and suitable green manuring to control these rots which the Canadian workers have found on strawberry, tobacco, tomato, lettuce and tulip, and all of which seem to be associated with the same group of fungi and nematodes. But the cause of this control is not known, so one cannot predict which root rots it will apply to. That it does not apply to all is shown by some results of G. H. Berkeley and L. W. Koch,[3] for they found a brown root rot of tobacco, also apparently caused by a complex group of organisms under conditions that are not yet known, was encouraged instead of discouraged by adding soybean tops to the soil.

Thus the present position is that a few isolated methods are available for combating root rots by modifying either the resistance of the root to infection or the microbial population in the rhizosphere outside the root; but the general principles underlying the methods are not yet understood, and the methods so far developed have only very limited applicability.

Specialised Associations between Plant Roots and Soil Micro-organisms

The presence of plant roots in a soil profoundly affects the general microbiological population in their neighbourhood as already discussed,

[1] V. C. Cochrane (*Phytopath.*, 1948, **38**, 185) found that red clover tops contain some soluble substance that turns radish roots brown, and hence presumably very liable to attack by these fungi. Soybean tops do not contain this substance.

[2] *Soil Sci.*, 1944, **58**, 473. [3] *Canad. Dept. Agric. Publ.* 667 (*Farmers' Bull.* 85), 1940.

but they can also affect a few groups specifically. Thus, as is described in Chapter 16, some soil-inhabiting bacteria can attack and enter the roots of certain species of leguminous, and perhaps other plants, multiplying inside them in specialised structures known as nodules and forming an association with the plant that usually increases its growth and vigour by their power of converting atmospheric nitrogen into a form available to the plant—an effect of very great agricultural importance. At least one species of actinomycetes may form a corresponding association with the alder,[1] but this association has received far less study than the leguminous.

Fungi have probably been living in close association with the roots of land plants ever since they evolved. When intermixed with algae they form lichens, but they occur in similar associations with the bryophytes pteridophytes and higher plants.[2] The association ranges from obviously parasitic through apparently neutral to obviously symbiotic,[3] and the degree of parasitism or symbiotism depends not only on the fungus, but also on the health and vigour of the plant, which, in turn, depends on the soil conditions and the climate. The fungi concerned fall into three groups: firstly, the specialised parasites that merely exist in the soil and only develop when plant roots approach them—they attack and enter the roots and then live entirely within the plant; secondly, a large group of soil-inhabiting fungi, only some of which are recognised as capable of being serious plant pathogens and which have been described in the previous section; and, finally, specialised fungi, often only capable of growing in the soil near a plant root, which develop extensively in and around the cortical root cells and in many cases are eventually digested by them. The individual hyphae of this group usually live simultaneously in the soil and in the root, and the group itself is known as mycorrhiza formers. This association is of proved benefit to some plants, but its effect on others is still unproven.

The mycorrhizal associations can conveniently be grouped into four classes: those mainly between some higher Basidiomycetes and Ascomycetes with the roots of many forest trees; those between perfect and imperfect Basidiomycetes with orchids; those between a group of fungi and ericaceous plants, neither of which will be considered here; and those between a very characteristic fungus and most types of higher plants growing in suitable conditions.

[1] M. Roberg, *Ber. deut. bot. Ges.*, 1934, **52**, 54; *Jahrb. Bot.*, 1934, **79**, 472; 1938, **86**, 344; O. von Plotho, *Arch. Mikrobiol.*, 1941, **12**, 1.

[2] For a general review of the mycorrhizal associations, see M. C. Rayner, *Mycorrhiza*, New Phytologist Reprint, No. 15, 1927; *New Phytol.*, 1926-7, **25** and **26**. For a recent review, see J. L. Harley, *Biol. Rev.*, 1948, **23**, 127.

[3] For illustrations of this, using cytochemical criteria, see D. T. MacDougal and J. Dufrenoy, *Plant Physiol.*, 1946, **21**, 1.

THE ECTOTROPHIC MYCORRHIZAS OF FOREST TREES

Some fungi form characteristic root associations with many groups of forest trees, forming short much-branched structures on their sub-lateral roots which take the place of root hairs, as is shown in Plates X and XI for Scots pine and the date palm. This structure is composed both of a mantle of fungus mycelium outside these roots, whose cortical cells are enlarged, and also of fungal hyphae filling the intercellular spaces, as can be seen from the cross-section of a mycorrhiza reproduced in Plate XI. The mantle is often coloured, the colours ranging from white through golden brown to black, and usually has a fairly smooth surface, though it may be loose and have many hyphae radiating from it into the soil.[1] It is these structures that were initially called mycorrhiza, or fungus roots, by B. Frank.[2] The type here described, characterised by a fungal mantle and the fungal hyphae filling the intercellular spaces, is termed ectotrophic, but there is a more common type to be described later, the endotrophic, which has no definite mantle and the hyphae invade the cortical cells. There are also transitional types, particularly of the ectotrophic, where some hyphal penetration of the cell takes place, known as ectendotrophic.

Mycorrhizas are typically ephemeral structures lasting only a growing season. Infection takes place when the sub-laterals send out their new short roots, from living fungal mycelium or spores in the soil produced there in the preceding autumn, and the structures are usually dead by the end of the growing season.

The trees which can carry these mycorrhizas include the Abietineae —the firs, pines, spruces and larches; the Betulaceae—the birch, alder, hazel and hornbeam; the Fagaceae—the beech, oak and chestnut; and the Salicaceae—the poplars and willows, as well as a few other trees, such as elm and hickory. The fungi are mainly Hymenomycetes, such as species of *Boletus*, *Amanita*, *Lactarius*, among others, but include at least one member of the Gasteromycetes (puff balls), *Rhizopogon*, and by inference truffles and truffle-like fungi, such as some of the *Tuberales* and *Elaphomyces* belonging to the Ascomycetes, as well as several fungi whose systematic position is not known as their fruiting bodies have not yet been observed.[3] Normally, a given species of fungus can form mycorrhiza on a number of species of tree, and, conversely, a single tree can carry mycorrhiza formed from a number of fungal species.

[1] For descriptions and photographs of some of these different types of mycorrhiza, see M. C. Rayner, *Trees and Toadstools*, London, 1945; E. Melin, *Medd. Skogsförsöksanst.*, 1927, **23**, 433; E. Björkman, ibid., 1941, **32**, 22.

[2] *Ber. deut. bot. Ges.*, 1885, **3**, 128. Frank spelt the word mycorhiza.

[3] E. Melin, *Handb. d. biolog. Arbeitsmeth.*, Abt. XI, Teil 4, pp. 1015–1108 (1936), gives lists of fungi forming mycorrhiza on various trees.

The mycorrhizal association is probably essential for most of these fungi, as they only grow, or at least only form their fruiting bodies profusely in the immediate neighbourhood of the tree root.[1] The contribution of the tree to the nutrition of the fungus is not known in detail, but it includes growth-promoting factors such as aneurin[2] and some phosphatides:[3] it almost certainly does not include any appreciable proportion of the fungus nitrogen supply—the fungus, in fact, supplies the tree with nitrogen rather than inversely—and it may include a proportion, and perhaps sometimes an appreciable proportion, of the carbohydrate requirements of the fungus. But this problem of the source of the energy supply to the fungus has not yet been definitely settled, for it is not yet known how far the fungus can obtain any of its energy supply from the soil organic matter.

There is much evidence that the fungus makes considerable demands on the carbohydrates produced by the tree. In the first place normal mycorrhizal infection only takes place when the plants are photosynthesising. Thus seedling roots only become infected after the leaves have opened[4]—an observation exactly analogous to that in leguminous crops, whose roots only become infected with nodule bacteria after the first true leaves have opened (p. 316). Further, E. Björkman[5] has shown that the number of mycorrhiza on pine and spruce seedlings increases as the carbohydrate content of the root increases; and indeed he considers that the root is only susceptible to infection when protein synthesis lags behind carbohydrate synthesis for any reason—as, for example, lack of available nitrogen or phosphate in the soil or the presence of climatic conditions conducive to rapid rates of photosynthesis.

This evidence shows that in the early stages of attack the fungus is probably mainly dependent on the plant for its carbohydrate supply, and this is further borne out by the observation that the mycorrhiza formers differ in their nutrition from the related Basidiomycetes in only being able to obtain their energy supply from simple carbon compounds such as sugars and mannitol, though a few can use starch with difficulty,[6] whilst the non-mycorrhizal fungi can use celluloses and some even lignin.[7] Further, the spores of the mycorrhiza-forming fungi will only germinate in the presence of complex growth-promoting

[1] L. G. Romell, *Svensk. Bot. Tidskr.*, 1938, **32**, 89; *Ecology*, 1939, **20**, 163.
[2] E. Melin and G. Lindeberg, *Bot. Notiser*, 1939, 241.
[3] E. Melin, *Untersuchungen über die Bedeutung der Baummycorrhiza*, Jena, 1925.
[4] M. A. Huberman, *Ecology*, 1940, **21**, 323 (for various species of pine); J. L. Harley, *Biol. Rev.*, 1948, **23**, 127 (for beech).
[5] *Medd. Skogsförsöksanst.*, 1941, **32**, 23; *Symb. Bot. Upsaliens.*, 1942, **6**, 1; *Svensk. Bot. Tidskr.*, 1944, **38**, 1.
[6] E. Melin, *Untersuchungen über die Bedeutung der Baummycorrhiza*, Jena, 1925; J. E. How, *Ann. Bot.*, 1940, **4**, 135.
[7] G. Lindeberg, *Symb. Bot. Upsaliens.*, 1948, **8**, 2; *Bot. Arch.*, 1947, **33**, No. 10; G. C. M. Harris, *Ann. Appl. Biol.*, 1945, **32**, 38.

factors, not all of which have been isolated, whilst those of the non-mycorrhizal fungi germinate much more easily.[1]

L. G. Romell[2] considers that the fungi rely on the tree for their carbohydrate supply all through the season, for he has found that many mycorrhizal fungi can only form their fruiting bodies when the tree they are attacking is fairly well grown, and he interprets this as showing that the fungus must make heavy demands on the tree's supply of carbohydrates in order to form its fruiting bodies. He quotes[3] an observation of P. Larsen in Denmark, who found that the fruiting bodies of a single species of a hymenomycete mycorrhiza-former on spruce contained 160 lb. of dry matter and $4\frac{1}{2}$ lb. of nitrogen per acre, and he estimated that the fungus would need at least 350 lb. of carbohydrate per acre to produce this crop of fruiting bodies, which is equivalent to about one-quarter of the carbohydrate used by the spruce to form new timber growth.

On the other hand there is some evidence that the fungi obtain at least part of their energy from the soil humus. Thus isolated fruiting bodies of typical mycorrhizal fungi can be found apparently unattached to any tree, though the possibility of them attacking other plants in their neighbourhood cannot be entirely ruled out. Again, as will be discussed shortly, the fungus seems to supply the tree with the greater part of its nitrogen supply when the level of ammonium or nitrate nitrogen in the soil is low. Unfortunately it is not known what forms of nitrogen besides ammonium the fungus will take up, but it is possible that a part of its supply is derived from the organic matter by direct decomposition brought about by the fungus. In the same way it supplies the plant with much of its phosphate, and some of this may also be directly obtained from the organic matter.

The fungus cannot properly be considered parasitic on the tree merely because it derives its energy supply from it; it should rather be looked upon as an extension of the tree's root system, supplying the tree with water and mineral nutrients derived from the soil, but obtaining the energy required for this from the tree itself. It is even possible that the fungus takes less energy from the tree to do this than would the uninfected roots.

The mycorrhizal association, on the other hand, is not essential for the trees, since they grow most vigorously in fertile soils when their roots carry few, if any, mycorrhizas.[4] But it benefits them in many natural conditions, particularly if the humus of the forest floor is of the

[1] N. Fries, *Svensk. Bot. Tidskr.*, 1942, **35**, 151; *Symb. Bot. Upsaliens.*, 1943, **6**, 4.
[2] *Svensk. Bot. Tidskr.*, 1938, **32**, 89; *Ecology*, 1939, **20**, 163.
[3] *Svensk. SkogsvFören. Tidskr.*, 1939, **37**, 348.
[4] H. L. Mitchell, R. F. Finn and R. O. Rosendahl, *Black Rock Forest Pap.* No. 10, 1937. See also J. L. Harley, *J. Ecol.*, 1937, **25**, 421.

mor or raw humus type, for then practically every organ carried by the shallower sub-lateral roots is a mycorrhiza, and there are many natural forest soils known that only allow good tree growth when the soil conditions have been so altered that mycorrhizas develop freely on the tree roots.

Mycorrhizas only develop freely on trees under three fairly definite soil conditions. They need a supply of organic matter, so develop most freely in the surface litter of the forest floor,[1] and can often be encouraged in a mineral soil by adding leaf litter or compost. They need well aerated soils and are inhibited by water-logging both through lack of oxygen and also by the presence of sulphides and other by-products of reducing conditions.[2] Sandy soils are more conducive to mycorrhiza formation than clays or peat bogs; but loosening a heavy soil or draining a bog, by increasing the soil aeration, increases the mycorrhizal development. They also need a restricted, but not too restricted, supply of nutrients, and in fact mycorrhiza formation appears to be the tree's response to low availability of nutrients.

There are many soils in the world that are too poor in phosphates, and there are even soils too low in available nitrogen to carry mycorrhizas: merely adding phosphates[3] in the form of superphosphates or basic slag in the one case, or available nitrogen in the form of ammonium nitrate,[4] for instance, in the other, results in a great development of mycorrhizas on the tree roots and, in consequence, a great increase in tree growth and vigour. On the other hand, adding a balanced fertiliser, or the nutrient in shortest supply, provided it is not in too short supply, may decrease mycorrhizal development.

Mycorrhizas benefit the tree by having a greater ability than the uninfected tree roots to extract plant nutrients, and possibly also water,[5] from the soil. This is illustrated in Table 44 which shows how the mycorrhizal association increases the nutrient uptake of pine seedlings compared with uninfected roots growing under comparable conditions; and it also shows that if the soil is well supplied with available nutrients, the uninfected roots can take them up quite easily. This last remark may not, however, apply to all trees, for A. L. McComb and J. E. Griffith[6] found that uninfected roots of Douglas fir had little power to take up even readily available phosphate. Over the greater part of the afforested areas in the world, however, the mycorrhizal association appears to be

[1] See R. Paulson (*Trans. Brit. Mycol. Soc.*, 1924, **9**, 213) for photographs showing this concentration of mycorrhiza in the leaf litter.
[2] W. N. Jones, *J. Agric. Sci.*, 1941, **31**, 379.
[3] See, for example, A. L. McComb, *Iowa Agric. Expt. Sta., Res. Bull.* 314, 1943.
[4] H. Hesselman, *Medd. Skogsförsöksanst.*, 1937, **30**, 529.
[5] J. L. Harley, *J. Ecol.*, 1940, **28**, 107; D. A. Cromer, *For. Bur. Aust., Bull.* 16, 1935.
[6] *Plant Physiol.*, 1946, **21**, 11.

the mechanism through which either phosphates from relatively unavailable forms, or nitrogen from organic compounds, are transferred from the soil to the tree.

TABLE 44

Effect of Mycorrhiza on the Mineral Nutrition of Pine growing in Poor Soil

Per seedling	White Pine[1]					Virginia Pine[2] on Iowan prairie soil	
	Sampled 10/6/36		Sampled 20/8/36				
	Non-mycorrhizal	Mycorrhizal	Non-mycorrhizal	Mycorrhizal	Non-mycorrhizal on soil with complete fertiliser	Non-mycorrhizal	Mycorrhizal
Dry weight in mgm.	160	208	181	337	550	152	323
Nitrogen content as per cent of dry weight	1·23	1·48	1·20	1·60	2·50	1·88	1·78
in mgm.	1·98	3·09	2·17	5·39	13·75	2·87	5·75
Phosphorus content, as per cent of dry weight	0·08	0·13	0·07	0·21	0·24	0·097	0·184
in mgm.	0·13	0·27	0·13	0·72	1·32	0·15	0·60
Potassium content, as per cent of dry weight	0·55	0·50	0·45	0·63	1·10	0·63	0·66
in mgm.	0·88	1·03	0·81	2·12	6·05	0·96	2·17
Number of mycorrhizal roots	—	—	—	—	—	7	350
Number of non-mycorrhizal roots	—	—	—	—	—	279	321

The root system of many trees that normally carry mycorrhizas are very inefficient extractors of soil phosphates compared with agricultural crops. Thus, A. L. McComb[3] found that by adding phosphate to an Iowan prairie soil the growth of jack pine seedlings, as measured by their weight, was increased twenty-eight-fold, whilst that of oats in the same soil was only increased by 80 per cent, and this increase in the jack pine was brought about through the phosphate stimulating a soil-inhabiting fungus to become mycorrhizal. Table 44 also shows that the beneficial action of the mycorrhizas in the two soils there used was mainly through the increased uptake of phosphate they cause.[4] The uninfected root systems of the trees are also unable to extract enough nitrogen from soils

[1] H. L. Mitchell, R. F. Finn and R. O. Rosendahl, *Black Rock Forest Pap.* No. 10, 1937.
[2] A. L. McComb, *J. Forestry*, 1938, **36**, 1148.
[3] *Iowa Agric. Expt. Sta., Res. Bull.* 314, 1943.
[4] R. O. Rosendahl (*Proc. Soil Sci. Soc. Amer.*, 1943, **7**, 477) showed mycorrhiza on pine could also extract more potash from orthoclase than uninfected roots.

high in organic matter but very low in ammonium or nitrate nitrogen.[1] Thus tree roots in a well-drained raw humus or mor layer, which is characterised by a low mineral nitrogen content and by a thin layer of high microbial activity, can only obtain an adequate nitrogen supply through the agency of the mycorrhizal fungus; for the fungus can either extract nitrogen direct from the organic matter or its mycelium, by ramifying through the mor layer, or can take up appreciable amounts of ammonium nitrogen even though it is only present in a very low concentration. On the other hand mull soils, which have a deeper layer of high microbial activity, typically contain an appreciable concentration of nitrate nitrogen, so the trees do not need the fungus for their nitrogen supply and, provided the phosphate supply is not too low, their roots will only carry a few mycorrhiza.

Mycorrhizas possess this ability to extract more nutrients from the soil than the tree roots for several reasons. They have a far larger absorbing surface than the root, for uninfected short roots rapidly become suberised except at their tips, and hence have only very little surface available for absorption, whilst mycorrhizas are not only fatter and more branched, but also delay the onset of suberisation of the root cells. They therefore tend to benefit the tree more towards the end of the season than the beginning by this power of keeping the roots physiologically young, as is shown in Table 44. Further, fungal hyphae frequently radiate from the mycorrhizas into the soil, which again effectively increases the absorbing area of the root system. These two effects allow the tree to absorb more water from the soil, and hence more nutrients, and this, as suggested by E. Stahl[2] and A. B. Hatch,[3] may be an important means by which mycorrhizas obtain additional nutrients.

Mycorrhizas may also be better extractors of nutrients from the soil than uninfected tree roots for three other reasons. Firstly, they can have a higher rate of CO_2 production than uninfected roots, and may even excrete organic acids, and each of these effects will increase the solubility of phosphates and also of iron compounds in their neighbourhood, and this effect appears to be more important in acid than in neutral soils.[4] Secondly, the fungal component may be able to compete more effectively than can the plant roots with the general microbial population for the nutrients in short supply. Thirdly, if the mycorrhizal fungus can decompose some of the organic matter in the litter, it can extract nutrients directly from it, instead of only using those excreted by the general saprophytic population.

[1] E. Melin, *Untersuchungen über die Bedeutung der Baummycorrhiza*, Jena, 1925.
[2] *Jahrb. f. wiss. Bot.*, 1900, **34**, 534.
[3] *Black Rock Forest Bull.* 6, 1937.
[4] J. B. Routien and R. F. Dawson, *Am. J. Bot.*, 1943, **30**, 440.

ENDOTROPHIC MYCORRHIZAS

The endotrophic mycorrhizas are far more widespread than the ectotrophic just described. They rarely have characteristic root forms—though the mycorrhizas on ericaceous plants are outstanding exceptions to this[1]—so their presence can only be recognised from a microscopic examination of root sections. They may, however, cause dwarfing and profuse branching of the rootlets carried by the main lateral roots of trees.[2] The fungi producing this widespread type of mycorrhiza cannot easily grow outside the living plant, and have not been observed to form fruiting bodies, nor have their range of host plants been investigated by pure culture inoculations. Hence, practically nothing is known about the number of strains that exist, and only little about their taxonomy.[3] The typical fungi are phycomycetes, classified in the genus *Rhizophagus*, which is probably related to the *Endogonaceae*. The fungus winters in the soil, attacks the plant roots when growth starts in the spring, and sends hyphae through and around the cortical and epidermal cells, but only rarely into the endodermal cells and practically never into the vascular tissues. The hyphae in some of the cells can take very characteristic shapes, such as vesicles or bladder-like organs, shown in Plate XII, and arbuscules or cauliflower-like organs composed of fine tufts of hyphae, shown in Plate XII, the latter typically occuring in cells near the endodermis. Hence, this group of fungi are often referred to as the vesicular-arbuscular type of mycorrhizal fungi. The vesicles seem to be of universal occurrence, both in the cells themselves and in the soil, and are probably storage organs for fatty substances when first formed. Arbuscules are of more erratic distribution—they are often absent in published descriptions—and rapidly undergo intracellular digestion as is shown in Plate XII. A third type of intracellular occlusion, known as pelotons, consist of coils or skeins of hyphae, and are illustrated in Plate XII, but these probably more often belong to a weakly parasitic *Rhizoctonia* than to a true mycorrhizal fungus. Typically, all the infected rootlets have died by the end of the growing season.

This association can presumably have the same function as ectotrophic mycorrhizas under some conditions and for some plants, but very little quantitative work has been done on it. It has not yet been demonstrated, for example, that its mycelium extends from the root cells into the soil. It is probably exactly analogous to the ectotrophic for some forest trees, such as the cypress, thuja and yew, among the conifers, and the ash, walnut, sycamore and poplar among the deciduous.

[1] For a description of these, see R. Friesleben, *Jahrb. wiss. Bot.*, 1934, **80**, 421, and 1935, **82**, 413; H. F. Bain, *J. Agric. Res.*, 1937, **55**, 811.

[2] H. Bouwens, *Zbl. Bakt.* II, 1937, **97**, 34.

[3] For a recent account of the taxonomy of this group, see E. J. Butler, *Trans. Brit. Mycol. Soc.*, 1939, **22**, 274.

B. Peyronel found it on nearly all alpine meadow plants, and W. D. Thomas,[1] in Colorado, found it extensively on plants growing above 7,500 feet, but much less commonly below 5,000 feet, observations which suggest it flourishes under conditions of low availability of nutrients, though this cannot be deduced from them. G. Samuel[2] found it extensively on plants growing in phosphate-deficient soils of South Australia, and it was particularly strongly developed on oats growing in manganese-deficient soils.

This association is also commonly found on the roots of a number of trees and shrubs of commercial importance, including the fruit trees, fruit bushes and strawberries of the north temperate regions, and citrus, coffee, tea and rubber in the tropics and sub-tropics, and also on many leguminous plants. Its significance is entirely unknown for most of these crops, though there is no reason to suppose that, when it is beneficial, it differs from ectotrophic mycorrhizas. It does, however, appear to differ in the greater ease with which it can become parasitic if its host plant loses vigour for any reason. Thus, H. S. Reed and T. Frémont[3] found citrus roots in some Californian orchards carried numerous mycorrhizas which were perfectly normal in healthy trees, but were parasitic in trees growing in unfavourable soil conditions. F. R. Jones[4] found leguminous plants, particularly those with a thick cortical layer of cells in their rootlets, such as the clovers, lucerne and peas carried extensive mycorrhizas, which did not appear to affect nodulation early on in the season. But these mycorrhizal rootlets tended to die off before uninfected rootlets, with the consequence that plant growth was brought to a standstill sooner than on those plants not carrying mycorrhizas.[5] Thus some varieties of lucerne in Wisconsin made practically no growth in late summer as the larger part of their transient rootlets had become mycorrhizal in late spring and were dead by midsummer, leaving practically no absorbing rootlets to produce late summer growth.

The endotrophic mycorrhiza can also be harmful if it weakens the roots sufficiently to allow pathogenic fungi to enter. Peyronel found that the mycorrhizal roots of many plants he examined usually carried a subsequent infection by *Rhizoctonia*, which are weakly pathogenic soil-inhabiting fungi. Strawberries have furnished an excellent example of this effect. At first the mycorrhizal fungus was suspected of being entirely harmful to strawberry plants by its action in depleting the cortical root cells of starch and weakening them so much that the pathogenic soil fungi—*Fusarium*, *Pythium*, *Rhizoctonia*, etc.,

[1] *Phytopath.*, 1943, **33**, 143.
[2] *Trans. Roy. Soc. S. Aust.*, 1926, **50**, 245.
[3] *Phytopath.*, 1935, **25**, 645; and see *Rev. d. Cytologie*, 1935, **1**, 327, for excellent drawings and photographs of the mycorrhizas.
[4] *J. Agric. Res.*, 1924, **29**, 459.
[5] *J. Amer. Soc. Agron.*, 1943, **35**, 625.

could gain entry and so cause serious root rot.[1] A. A. Hildebrand[2] was able to show, however, that healthy and vigorous strawberry plants also carried these mycorrhizas, but were sufficiently active to provide enough carbohydrate for the fungus without weakening its root system: it was only when they were unable to produce enough carbohydrate for the fungus that it became parasitic.

It is not easy to distinguish between endotrophic mycorrhizal and other fungi in plant roots, as not enough is known about the effects of light infection by these other fungi. But typically they differ from the mycorrhizal in their simpler food requirements: they can usually be grown in pure cultures whereas the mycorrhizal fungi either do not grow at all, or else only very slowly; they often cause discoloured spots on the outside of the infected root, due to necrosis of the cells they attack, whilst the mycorrhizal fungus merely causes a slight yellowing of these cells; and their intracellular mycelia do not usually suffer digestion easily, nor do they usually form organs of large surface, such as arbuscules in the cell, though *Rhizoctonia* may produce pelotons which should be susceptible of digestion, though this only seems to have been described in some orchids,[3] which differ from the other mycorrhizal plants by being definitely parasitic on the fungus.

[1] D. G. O'Brien and E. J. McNaughton, *West of Scot. Agric. Coll., Res. Bull.* 1, 1928; J. H. L. Truscott, *Canad. J. Res.*, 1934, **11**, 1.
[2] *Canad. J. Res.*, 1934, **11**, 18; with L. W. Koch, ibid., 1936, **14** C, 11.
[3] A. Burgess, *New Phytol.*, 1939, **38**, 273.

CHAPTER XIV

THE DECOMPOSITION OF PLANT MATERIAL

The Plant Constituents

THESE FORM THE primary material both for the food of the soil organisms and for the production of soil organic matter. They can be divided up into three main groups of material: the cell contents, the reserve food supply, and the cell wall and structural material. The first group is rich in proteins and sugars, and the second in starches, fats and proteins. The third group consists of two fairly distinct materials, the skeletal framework and cementing and encrusting substances.

The skeletal framework is built up from cellulose and cellulosan fibres. Pure cotton cellulose consists of chains of glucose residues linked at the 1 : 4β positions, as shown in Fig. 18, but structural cellulose also contains some xylose and glucuronic acid residues similarly linked in the glucose residue chain.[1] The cellulosans of the angiosperms are shorter chains, mainly of xylose and a few uronic acid residues similarly linked, as in Fig. 18, but in the gymnosperms there are also chains of mannose residues, but their linkage has not been definitely established. The architecture of the skeletal framework is still under discussion; it is probably built up of micelles containing about a hundred oriented cellulose chains, each containing several hundred glucose residues with up to 20 to 30 per cent by weight of shorter cellulosan chains similarly oriented.[2]

The cementing and encrusting material consists of two distinct groups of substances: polymerised sugar units and the lignins. The former predominates in the young shoot but the latter in the mature. Initially the lignin only covers the cell walls and the outside of the cellulose micelles, but as the tissue matures it may encrust the fibres in the micelle also. The carbohydrates are normally arbitrarily divided into those substances soluble in water or dilute acids—the pectins, gums and mucilages —and those soluble in dilute alkali—the hemicelluloses—though this group contains some of the cellulosans already mentioned. These substances are built up of either glucose and the corresponding glucuronic

[1] A. G. Norman, *Biochem. J.*, 1936, **30**, 2054; with W. H. Fuller, *J. Bact.*, 1943, **46**, 281; S. P. Saric and R. K. Schofield, *Proc. Roy. Sci.*, 1946, **185** A, 431.

[2] See K. H. Meyer, *Natural and Synthetic High Polymers*, New York, 1942, for a description of the present-day views on the constitution of cellulose, and A. G. Norman, *The Biochemistry of Cellulose, the Polyuronides, Lignin, etc.*, Oxford, 1937, for a general discussion of these problems. For a recent review of the chemistry of the polysaccharides, see A. G. Norman, *Ann. Rev. Biochem.*, 1941, **10**, 65.

acid and xylose residues, or else galactose and the corresponding galacturonic acid and arabinose residues, though mannose and other residues sometimes occur. The gum molecules[1] have probably short main chains with many shorter side-chains; pectin is possibly long chains of galacturonic acid residues linked through the 1 : 4α positions, as in starch; and the hemicelluloses short chain molecules containing an appreciable proportion of pentose and uronic acid residues. But our

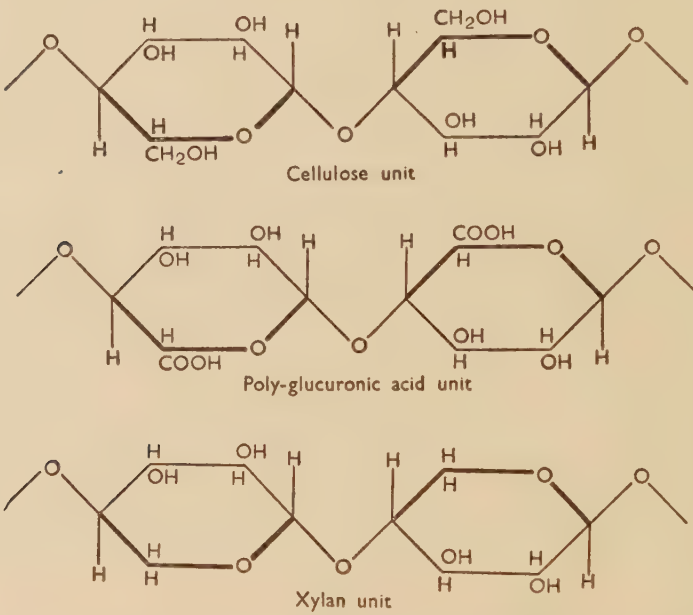


Fig. 18. Formulae of chains built from glucose units through 1:4β linkages.

knowledge of these substances is imperfect, and there are not yet any accepted methods in general use for separating and purifying the individual hemicelluloses, so that the interpretation of experimental results is complicated by the possibility that other molecules may be present besides the type under investigation.

Two of the constituents can, however, be readily determined by boiling the material with 12 per cent hydrochloric acid—the pentose sugar and the uronic acid contents. The former yields furfuraldehyde, which can be distilled off and estimated;[2] and the carboxyl group of the latter is split off and appears as carbon dioxide. Uronic acids,

[1] For a recent review of the constitution of plant gums, see E. L. Hirst, *J. Chem. Soc.*, 1942, 70.

[2] For an example of the precautions necessary for the determination of hemicelluloses, see A. G. Norman, *Biochem. J.*, 1929, **23**, 1353.

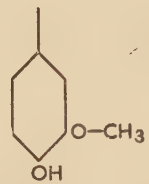
unfortunately, are not the only acids that give the reaction,[1] but no other acid that does has been suspected or isolated in plant, compost or soil material.

Lignins are richer in carbon and poorer in oxygen than cellulose, their typical analyses being

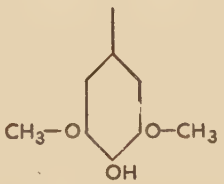
	Carbon	Hydrogen	Oxygen
lignin	61–64%	5–6%	30%
cellulose	44·5%	6·2%	49·3%

but the lignins of most agricultural crops differ from carbohydrates in containing nitrogen.[2] Thus the lignins of leguminous plants may contain up to 3 per cent, and whilst those of the grasses are usually lower, from 1·5 to 2·0 per cent, they overlap those of the legumes. The lignin of

Phenyl propane



Guaiacyl radicle



Syringyl radicle

cereal straw has, however, a much lower nitrogen content, 0·5 per cent being perhaps a typical figure. The lignins of wood have a still lower nitrogen content.

Lignins are composed of substituted phenyl-propane groups linked together.[3] The phenyl group has a hydroxyl in the *para*-position and often a methoxyl on the *meta*, in which case it is known as the guaiacyl radicle, and perhaps sometimes also a second methoxyl, as in the syringyl radicle. The propane may have a double bond, i.e. be a propene, and also a hydroxyl. The position of the nitrogen is unknown, but it is probably present as a tertiary amine in a linkage similar to that in pyridine. Bondi and Meyer claim to have shown that the lignins of grasses, cereals and legumes are built out of three of these units and hence have a molecular weight of about 650. Further, they showed that grass lignins contained two methoxyls and leguminous lignins one methoxyl per molecule whilst each contained two phenolic and one aliphatic hydroxyls. The third phenolic hydroxyl that should have been present presumably takes some part in the polymerisation process.

[1] A. G. Norman and J. T. Martin, *Biochem. J.*, 1930, **24**, 649.

[2] A. Bondi and H. Meyer, *Biochem. J.*, 1948, **43**, 258; E. R. Armitage, R. de B. Ashworth and W. S. Ferguson, *J. Soc. Chem. Indust.*, 1948, **67**, 241.

[3] For a recent review of the structure of lignins, see H. Hibbert, *Ann. Rev. Biochem.*, 1942, **11**, 183; E. G. V. Percival, *Ann. Rep. Chem. Soc.*, 1942, **39**, 142.

The Decomposition of Plant Residues

The biochemistry of the rotting of plant residues in the soil has not been followed in any detail because of the lack of suitable analytical methods, though the rotting or composting of plant residues, and particularly cereal straws, outside the soil has been studied in more detail. The interpretation of the analytical results is complicated both because of the deficiences in methods of analysis commonly employed, and also because the rotting process includes the synthesis of microbial protoplasm,[1] and the excretion of products of microbial metabolism, both of which may react in the same way to the analytical methods as some of the initial plant products. The difficulty can be serious for substances containing uronic acids or yielding furfuraldehyde on acid hydrolysis, i.e. products of the hemicellulose type; but it is greatest for the organic nitrogen compounds, and no attempt has yet been made to follow the course of their transformations during composting.

The general course of the decomposition of cereal straws under normal conditions is reasonably well understood. Initially, the hemicelluloses encrusting the cellulose fibres are strongly attacked, mainly by fungi, and this attack is accompanied by a considerable evolution of heat and carbon dioxide. The most prominent feature of the attack, once this initial stage is over, is the loss of cellulose, which accounts for the major part of the loss of organic matter. Thus, Norman,[2] working with oat straw rotting aerobically under favourable conditions, found that 100 gm. of oat straw, containing 23 per cent of free hemicelluloses and 44 per cent of pure cellulose, lost 10 gm. of hemicellulose and under 1 gm. of cellulose in the first four days, an additional 1·5 gm. of hemicellulose and 4 gm. of cellulose in the next four, and an additional 1·25 gm. of hemicellulose but 11 gm. of cellulose in the next eight days; the maximum temperature was reached on the seventh day, but the maximum rate of heat production occurred between the second and sixth days. The reason for the slowing down in the rate of hemicellulose decomposition when only half has disappeared is presumably due to the inhomogeneity of this fraction. Finally, the products of microbial activity appear to be the main products undergoing decomposition (Table 45).[3]

A well-rotted compost contains little hemicellulose or cellulose, but the relative times taken for these two constituents to fall to a low level depends on circumstances. Norman[4] found that a chaffed oat straw, rotting at 35° C. under good conditions, lost 99 per cent of its

[1] For a recent account of the composition of the body substances of bacteria, see J. R. Porter, *Bacterial Chemistry and Physiology*, New York, 1946.

[2] *Ann. Appl. Biol.*, 1930, **17**, 575.

[3] A. G. Norman, *Biochem. J.*, 1929, **23**, 1367.

[4] *Biochem. J.*, 1932, **26**, 573.

hemicelluloses, but only about a third of its celluloses in nine months' decomposition, but Waksman's[1] results on the whole indicate that the celluloses usually fall to a low level before the hemicelluloses. The cause of the discrepancy is not known, but may lie in the different methods used to determine cellulose and hemicellulose.

TABLE 45

The Disappearance of Hemicelluloses and Celluloses from Rye Straw during Aerobic Decomposition

Temperature of decomposition 35° C. Extra nitrogen added as ammonium carbonate

All weights calculated on the quantities initially present in 100 gm. organic matter

Duration of decomposition in days	0	4	8	24	84
Organic matter	100	97	78	62	49
Cellulose	48	47	33	25	20
Associated Xylan	9·0	9·1	8·9	5·4	4·2
Groups in the Hemicellulose fraction:					
Uronic acid	4·5	4·2	3·0	2·3	1·8
Anhydropentose	17·0	13·8	7·4	5·5	4·2
Pectin as calcium pectate	0·35	0·35	0·41	0·62	0·85

The course of the lignin decomposition has not been followed in any great detail because of the difficulty of finding specific tests for lignin. Lignin only decomposes slowly, and its rate of decomposition depends on its composition and on its admixture with other hemicelluloses; thus, J. P. Martin and Y. Wang[2] have shown that the lignins in timothy and clover hay appear to decompose more easily than those in oat or maize straw. The importance of the lignin fraction in decomposition lies in the fact that it renders some of the cellulose and possibly other constituents inaccessible to the microflora, hence the higher the lignin content of the material the greater is the proportion of cellulose that is encrusted with lignin and the slower is its decomposition. Thus, 15 per cent of lignin seriously reduces the rate of decomposition of cellulose; 20 to 30 per cent, as is common in woods, slows up the decomposition so much that they cease to have any agricultural value

[1] See, for example, S. A. Waksman and F. C. Gerretsen, *Ecology*, 1931, **12**, 33; S. A. Waksman and F. G. Tenney, *Soil Sci.*, 1929, **28**, 55; J. P. Martin and Y. Wang, *J. Amer. Soc. Agron.*, 1944, **36**, 373.

[2] *J. Amer. Soc. Agron.*, 1944, **36**, 373.

as a source of humus; and a content of around 40 per cent, as occurs in coir, renders the fibre extremely resistant to decomposition.[1]

The course of the decomposition depends on the relative rates at which the heat is produced and dissipated in the initial stages, for these determine the temperatures at which the decomposition takes place, and hence the composition and activity of the microflora. These relative rates are controlled by the decomposability of the substances, the water supply and the aeration; a moist, loose, well-aerated heap decomposes and produces heat more rapidly than a compacted badly aerated heap, but if the heap is too loose it will also lose its heat rapidly.

The effect of the temperature at which decomposition is taking place has not yet been worked out in detail. The general results seem to be that in the temperature range 5° to 30° C.,[2] the lower the temperature of decomposition the slower is the process, and after it has slowed down the smaller is the loss of organic matter and the higher is the organic nitrogen content of the compost. Low temperatures, in fact, as H. L. Jensen[3] has been able to show, directly encourage the accumulation of microbial protoplasm. At very high temperatures,[4] in the range 45° to 75° C., the loss of organic matter and the organic nitrogen content of the compost both decrease with increasing temperature, probably due to the increasing restriction of the microflora to specialised thermophilic organisms, and to their tendency to attack proteins rather than cellulose. In the range 30° to 45° C.,[5] increasing temperature may not have any marked effect on the loss of organic matter, but may allow the organic nitrogen content of the compost to increase.

The results are unfortunately not clear cut, and the effect of the maximum temperature reached during decomposition on the properties of composts and manures has not been properly worked out.[6] If high temperatures, over 60° C., for example, are reached, it is possible that the humus is formed with less loss of organic matter, and that it is more crumbly, contains fewer volatile substances, i.e. has no smell, and has a higher nitrogen content than if the maximum temperature only reached about 40° C.; and this is the principle used by H. Krantz in his method of composting fresh dairy manure by the hot fermentation or Edelmist process. On the other hand, if the maximum temperature is kept low,[7] possibly under 20° C., the loss of organic matter is reduced

[1] See, for example, W. H. Fuller and A. G. Norman, *J. Bact.*, 1943, **46**, 291; W. J. Peevy and A. G. Norman, *Soil Sci.*, 1948, **65**, 209.
[2] S. A. Waksman and F. C. Gerretsen, *Ecology*, 1931, **12**, 33.
[3] *Proc. Linn. Soc., N.S.W.*, 1939, **54**, 601.
[4] S. A. Waksman, T. C. Corden and N. Hulpoi, *Soil Sci.*, 1939, **47**, 83.
[5] A. G. Norman, *Ann. Appl. Biol.*, 1931, **18**, 244.
[6] See, for example, S. H. Jenkins, *Imp. Bur. Soil Sci., Tech. Comm.* 33, 1935; R. Junghähnel, *ForschDienst. Sonderh.* 17, 1941, 103; K. Maiwald, ibid., 45.
[7] R. M. Salter and C. J. Schollenberger, *Ohio Agric. Expt. Sta., Bull.* 605, 1939.

and the nitrogen content increased, which forms the basis of the cold fermentation method of strawy manure.

The nitrogen demands of the microbial population during decomposition are of obvious practical importance. On the whole, material containing less than 1·2 to 1·3 per cent nitrogen, on the dry weight basis, when rotting in the presence of ammonium salts will cause some of the ammonia to be taken up and converted into organic nitrogen compounds. If the material contains more than 1·8 per cent nitrogen, some of this nitrogen will be converted into ammonia during the rotting process, though if the nitrogen content is not much in excess

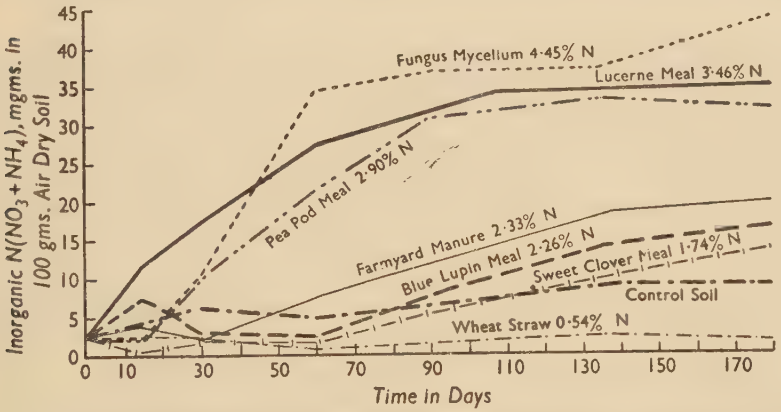


Fig. 19. Rate of accumulation of ammonia and nitrate in a loam soil to which 5 per cent of various organic substances have been added.

of this, ammonia may be taken up and fixed in the initial stages of the decomposition. Materials with intermediate nitrogen contents, between 1·2 and 1·8 per cent, tend to have no net effect on the level of ammonia during the decomposition, though they also often take up ammonia initially and release it again later.[1] Fig. 19, taken from some of H. L. Jensen's work,[2] illustrates these points. Thus, the rotting of nitrogen-poor plant or animal remains in a soil will lower its content of mineral nitrogen, i.e. ammonium and nitrate ions, whilst the rotting of a nitrogen-rich material will increase it. But these effects depend somewhat on the type of material being rotted, and neither the nitrogen content alone, nor the ratio of the carbon in the material to the nitrogen, is a safe guide to the effect of the rotting process on the mineral nitrogen level in the soil.

[1] For an example of this, see N. H. Parberry and R. J. Swaby, *Agric. Gaz., N.S.W.*, 1942, **53**, 357. I am indebted to Dr. R. J. Swaby for showing me a fuller report of these experiments containing the nitrogen contents of the various materials used. C. N. Acharya *et al.* (*Indian J. Agric. Sci.*, 1946, **16**, 178) obtained somewhat similar results.

[2] *J. Agric. Sci.*, 1929, **19**, 71.

An experiment of Waksman and F. G. Tenney[1] illustrates these effects well. They added ground-up plant roots of varying nitrogen content to a soil and measured its nitrate nitrogen content during decomposition. They added to 28 lb. of soil sufficient material to contain 600 mgm. of nitrogen, incubated it for three months, then leached the soil well and determined the nitrate nitrogen in the leachates. The results, which are given in Table 46, show that ground clover roots, with a nitrogen content of 1·7 per cent, contains just about enough nitrogen for its own decomposition, but the other plant roots remove nitrogen from the soil during this process.

TABLE 46

Relation between the Nitrogen Content of Various Plant Roots and the Nitrate Nitrogen in the Soil

Material used	Nitrogen content of material Per cent	Weight of material added Grams	Nitrate nitrogen in leachings Milligrams	Gain or loss of nitrogen Milligrams
Control soil . . .	—	—	947	—
Oat roots	0·45	133	207	—740
Timothy roots . . .	0·62	97	398	—549
Maize roots . . .	0·79	76	511	—436
Clover roots . . .	1·71	35	925	— 22
Dried blood . . .	10·71	5·6	1750	+803

The nitrogen demands during the rotting of a material can be specified by its nitrogen factor, which is defined as the number of grams of nitrogen, in the form of ammonium or nitrate ions, immobilised during the decomposition of 100 gm. of the material. The nitrogen factor, however, is not a constant for a given material, but depends somewhat on the conditions prevailing during the decomposition. However, E. H. Richards and A. G. Norman,[2] who introduced it to specify the amount of nitrogen that must be added to heaps of vegetable waste in the field to allow rapid decomposition, found that in farm practice it was sufficiently constant, both during the course of a rot and for a given material rotting in compost heaps under natural conditions, to be of practical value in farm advisory work. In the first place the nitrogen factor is not quite constant during the course of a rot, as is shown both in Table 47, taken from Richards and Norman's work, and also by the fact, already mentioned on p. 235, that materials with a small negative nitrogen factor may remove ammonium and

[1] *Soil Sci.*, 1927, **24**, 317. [2] *Biochem. J.*, 1931, **25**, 1769.

TABLE 47

Effect of Duration of Decomposition on the Nitrogen Factor of Oat Straw

Nitrogen content of straw, 0·30 per cent

Duration of decomposition in days	8	16	24	48
Per cent loss of organic matter	13	25	37	50
Nitrogen factor	0·75	0·67	0·75	0·80

nitrate nitrogen, if available, during the early stages of decomposition and release it later on. In the second place, the nitrogen factor of a given material cannot be predicted from its nitrogen content. It is usually higher for natural materials, such as straw, than for pure substances, such as cellulose or straw treated to remove some of its constituents, as is shown in Table 48. The nitrogen in a material

TABLE 48

Effect of Treating Straw on its Decomposability and Nitrogen Factor

Oat straw extracted with	Composition of straw					Decomposition for 48 days	
	Cellulose and associated cellulosans	Hemicellulose as uronic acid anhydride	Hemicellulose as anhydro-pentose xylose	Lignin	Per cent nitrogen	Loss of organic matter	Nitrogen factor
Control	49	5·4	11·5	18·5	0·30	50	0·80
Hot water	51	6·2	13·3	—	0·27	18	0·51
4 per cent NaOH	84	1·0	1·5	11·1	0·12	21	0·16
4 per cent alcoholic NaOH	66	3·2	7·5	8·2	0·11	21	0·36
2 per cent HCl	62	2·4	1·0	25·6	0·34	9	0·27

is not all equally available to micro-organisms: they may use ammonium salts, if present, in preference to difficultly available nitrogen compounds in the material. Thus, Richards and Norman found that bean husks, which had a nitrogen content of 3 per cent, rot to liberate ammonia in the absence of readily available nitrogen, but immobilise some nitrogen in its presence (Table 49).

The rate of decomposition of a material with a low nitrogen content can be increased considerably if a suitable source of nitrogen is added, for the nitrogen supply obviously limits the maximum amount of protoplasm that can be present, and, if it is too low, it limits biological

TABLE 49

Effect of Added Nitrogen on the Nitrogen Factor of Rotting Bean Husks

Nitrogen content of bean husks, 3 per cent. Duration of decomposition: 48 days

	Loss of organic matter	Nitrogen content of compost	Nitrogen factor
	per cent	per cent	
No added nitrogen . .	48	4·7	− 0·52
With added ammonia . .	41	5·4	+ 0·15

activity. The added nitrogen may also allow a larger proportion of the carbonaceous organic matter to be converted into microbial protoplasm or its by-products, hence it may increase the proportion of the added organic matter that is converted into humic substances.[1] This forms the principle underlying all processes for rapidly obtaining a compost or manure from straw without passing it through a stockyard.[2] Since its nitrogen factor is about 0·8, at least 18 lb. of nitrogen should be added per ton of straw to ensure its rate of decomposition is not limited by nitrogen shortage. This is commonly added as ammonium sulphate, but any other material rich in nitrogen, for example, urine, animal droppings, dried blood, leguminous hays or young green plant material, is equally suitable. It has been claimed that organic nitrogen compounds give a mellow and friable compost in contrast to inorganic nitrogen compounds, which give a more sticky compost, possibly because the former encourage a greater development of fungi compared to bacteria, but there is little critical evidence for this statement.

The actual amount of mineral nitrogen locked up when material with a low nitrogen content is decomposing depends on several factors, not all of which have been well established. For a given carbon and nitrogen content in the decomposing material, the amount of soil nitrogen locked up during the decomposition increases as the speed of decomposition increases. Hence, materials low in lignins typically immobilise more nitrogen than those high in lignins,[3] and decomposition in warm soils immobilises more nitrogen than in cool soils. Thus L. A. Pinck, F. E. Allison and V. L. Gaddy[4] found that under Maryland conditions a ton of wheat straw immobilised about 16 to 18 lb. of nitrogen if decomposing during the winter, but between 21 and 28 lb. during the summer. Again, decomposition under acid conditions

[1] F. J. Salter, *Soil Sci.*, 1931, **31**, 413.
[2] H. B. Hutchinson and E. H. Richards, *J. Min. Agric.*, 1921, **28**, 398.
[3] E. H. Richards and A. G. Norman, *Biochem. J.*, 1931, **25**, 1769; E. J. Rubins and F. E. Bear, *Soil Sci.*, 1942, **54**, 411.
[4] *J. Amer. Soc. Agron.*, 1946, **38**, 410.

appears to lock up more nitrogen than under neutral conditions,[1] though the significance of this result is not known.

The process of decomposition may lock up other nutrients besides nitrogen, or be retarded by their lack. The ash of microbial protoplasm may contain up to 25 per cent of phosphorus and 37 per cent of potassium,[2] so that the micro-organisms may compete with growing crops for the available supplies of these nutrients if the soil or the decomposing organic matter is very low in them. I. P. Mamchenko[3] has brought forward some evidence that increasing the phosphate supply of material well supplied with nitrogen, such as clover residues, increases the proportion of carbonaceous material converted to humic substances by reducing the proportion respired as carbon dioxide. There is also some evidence that the rate of decomposition of tree leaves depends on the base content of the leaves,[4] though whether this is due simply to the effect of the bases in controlling the *p*H of the rotting material and therefore the composition of the microflora, or to their nutrient effect on the micro-organisms has not been determined.

In conclusion, the conditions favouring rapid decomposition of plant products are:

1. The material should have a low lignin, and probably also a low wax, content.

2. The material should be in as fine a state of comminution as possible; and it is probable that the principal natural agents bringing this about are the larger soil animals.

3. There should be an adequate supply of available nitrogen.

4. The *p*H should not be allowed to fall too low, otherwise the microbial population becomes unduly restricted and the larger soil animals die out.

5. The aeration should remain good and the moisture supply adequate. Anaerobic conditions or water-logging lead to a restricted population, mainly bacterial, though the nitrogen demands of the population falls.

6. The temperature should be fairly high. Temperatures above 45° C. or below 30° C. give lower rates of decomposition than temperatures in this range.

7. For substances rather difficult to decompose, mixed groups of materials decompose quicker than single groups. Thus, in forest floors, mixed litter from several species of trees usually decomposes quicker than litter from a single type.[5]

[1] H. L. Jensen, *J. Agric. Sci.*, 1929, **19**, 71.
[2] S. A. Waksman, *Principles of Soil Microbiology*, 2nd ed., 1931, p. 367.
[3] *Vest. Udob. Agrotekh. Agropoch.*, 1941, No. 3, 5.
[4] W. M. Broadfoot and W. H. Pierre, *Soil Sci.*, 1939, **48**, 329.
[5] See, for example, J. T. Auten, *J. Forestry*, 1940, **38**, 229; F. G. Gustafson, *Plant Physiol.*, 1943, **18**, 704.

Composting

Composting is the term usually applied to the rotting down of plant and animal remains in heaps before the residue is applied to the soil. The chemical processes of decomposition in the compost heap and the soil differ in two respects: the compost heap is usually not so well aerated, and the temperature of the decomposition can be far higher in it than in the soil.

The points of importance in composting are ensuring that the water content and the aeration of the heap are within certain limits: in practice the rate and type of decomposition is controlled by varying the aeration conditions rather than the water content of the heap. If the heap is too dry, too compacted, or too water-logged, little decomposition takes place, and if it is kept moist and loose, decomposition is at its maximum.

There appears to be no virtue in rotting down materials in the compost heap compared with letting them rot down in the soil itself as far as adding plant nutrients to the soil or increasing its humus content are concerned. The relative value of the two methods depends on circumstances. One cannot always add farmyard manure or waste organic material to the soil when it is available: one must often leave it until it is convenient to put it on the field, and composting is a way of storing these materials until they are required. Again, some soils are naturally very open and free draining, and adding undecomposed material will often exaggerate the harmful consequences of this open structure. Under these conditions it is much preferable to add well-rotted humic material, for this will tend to reduce the openness of the soil. Again, an important difference between the unrotted plant material and the compost is in physical condition. The unrotted material typically holds little water and is coarse and fibrous; the compost holds much water and is friable. On light, sandy soils, which in any case are too open for optimum crop growth, a compost is obviously preferable on this score, whilst on some heavy soils the uncomposted material may be better.

A third difference lies in the consequence of decomposition. A compost, when added to a soil, continues its decomposition only slowly, whilst unrotted material, particularly if it is rather succulent, begins to decompose rapidly, with the consequence that the carbon dioxide content of the soil air is raised, which may be very beneficial on light soils (see p. 479)—that is, on just those soils whose physical condition is most benefited by adding compost. If the decomposition is too rapid, however, the carbon dioxide content of the soil air may rise so high, or the nitrates in the soil temporarily fall so low, that plant growth is inhibited.

A fourth factor, the importance of which has not yet been established, is that rotting a given amount of material in the soil will usually give a larger addition to the humus and nutrient content of the soil than if it is first composted and then added to the soil. Experiments have been made at Rothamsted for a number of years in which a given dressing of straw and nitrogen ploughed into the soil is compared with the same quantity of straw rotted with the same quantity of nitrogen in a compost heap and then applied to the land. The ploughed-in straw has always given a better yield than the compost, as is shown in Table 50.

TABLE 50

Comparison of Straw Composted with Straw Ploughed in on a Three-course Rotation at Rothamsted

	12 years, 1934–45			
	Year of applying straw		Year after application	
	Compost	Straw ploughed in	Compost	Straw ploughed in
Potatoes, tons per acre . . .	7·86	9·40	7·40	7·97
Sugar-beet, sugar cwt. per acre .	37·0	41·2	36·4	38·2
Barley, grain cwt. per acre . .	27·7	31·2	26·5	27·9

The cause of the better crop response to the rotting in the soil compared with rotting in the compost heap may be due to losses of nitrogen during the composting process. Thus C. N. Acharya and his co-workers[1] found that nearly one quarter of the nitrogen in a mixed organic refuse, whose C/N ratio was initially 32, was lost during the first 20 weeks of composting, probably mainly by volatilisation as ammonia, but there was no net loss if some soil was added to the refuse. Presumably the ammonia set free in the decomposition is absorbed by the clay in the soil and then nitrified.

Composting has, however, a considerable farm health aspect. It allows many parasitic organisms in the plant and animal material to be destroyed before the residues are put back on the land, and this destruction is more complete the higher the maximum temperature attained and the better the compost has been made. High temperatures have the further advantage that all the weed seeds present are also killed and decomposed. Hence, if possible trouble from either of these

[1] *Indian J. Agric. Sci.*, 1945, **15**, 214; 1946, **16**, 90.

sources is suspected, good high-temperature composting may be well worth while.

Finally, the effect of composting on the content of members of the vitamin B complex[1] and other growth-promoting substances, such as the auxins,[2] has been investigated by many workers, who all find that the amount of these substances in the heap decreases during the course of the decomposition. Composts are, therefore, not rich sources of these substances, but, as has already been mentioned on p. 25, there is no evidence that any farm crop benefits in any way by increasing the levels of these compounds in the soil.

The Micro-organisms involved in the Decomposition of Plant Remains

Many species of soil fungi, including members of the *Aspergilli*, *Penicillia* and *Trichoderma*, can decompose natural plant debris in pure culture and have therefore unspecialised food requirements (Table 51).[3] They can readily utilise purified sugars, starches and some hemicelluloses for their energy supply, though many grow better on cellulose in its natural admixture with hemicelluloses than on the highly purified material. None of these fungi in pure culture, however, can decompose plant material as rapidly as can a suitable mixed population.[4]

TABLE 51

Decomposition of some Plant Constituents brought about by Pure Cultures of Fungi and Actinomycetes

Oat straw rotting at 30° C. for 48 days. Extra nitrogen added as ammonium carbonate

All results are expressed on the basis of 100 gm. of straw

	Dry matter	Cellulose and associated xylans	Anhydro-pentose in hemi-cellulose	Uronic acid anhydride	Nitrogen factor	Per cent of organic nitrogen
Initial straw . .	100	53	14·4	4·8	—	0·31
Mixed microflora .	49	15	2·2	2·6	0·84	2·37
Aspergillus flavipes .	71	25	5·3	3·5	0·69	1·39
Trichoderma (sp.) .	73	33	9·9	2·6	0·73	1·42
Phoma (sp.) . .	74	29	5·4	3·0	0·50	1·07
Aspergillus niger .	87	42	10·2	3·2	0·82	1·30
Actinomycete (sp.) .	89	41	11·1	4·8	1·03	1.55

[1] R. L. Starkey, *Soil Sci.*, 1944, **57**, 247.
[2] J. H. Hamence, *J. Soc. Chem. Indust.*, 1945, **64**, 147.
[3] A. G. Norman, *Ann. Appl. Biol.*, 1930, **17**, 575; 1931, **18**, 244; 1934, **21**, 454.
[4] For another example, see S. A. Waksman and I. J. Hutchings, *Soil Sci.*, 1937, **43**, 77.

The fungi are probably also the predominant lignin-decomposing organisms. Filamentous fungi can certainly decompose the lignins of straws and leafy plant material, but where lignin-rich residues accumulate, as, for example, on forest floors, the higher basidiomycetes seem to be the dominant decomposers.

The fungi attack all the constituents of the plant debris at the same time, and though they can obtain part of their energy supply by decomposing the lignin, most species must also obtain part from more readily decomposable material. Some hymenomycetes however, such as the mushroom *Psalliota* (*Agaricus*) *campestris*,[1] appear to use lignins in preference to the polysaccharides. G. C. M. Harris[2] found that this was also true of *Marasmius peronatus* when growing in beechwood litter, but this is probably not a general property of this fungus, for G. Lindeberg[3] found that it attacked the polysaccharides as well as the lignin of pine litter. The higher hymenomycetes may be very selective in their food requirements, for V. Y. Chastukin[4] found that on the forest floor pine twigs and needles and birch twigs and leaves each carried its own characteristic group of fungi.

Some species of actinomycetes seem to behave like soil fungi, in that they are unspecialised feeders on plant remains, though initially they may not utilise hemicelluloses or celluloses quite as easily as fungi. Norman found those he was working with had relatively little power to decompose purified hemicelluloses, but S. A. Waksman and R. A. Diehm[5] worked with some that could be trained to grow readily on these purified substances.

The power of bacteria to attack plant constituents depends on the aeration. Under partially anaerobic conditions, many pure cultures of bacteria can attack celluloses and hemicelluloses, either in their natural condition or when purified, provided an adequate supply of organic nitrogen compounds and growth-promoting substances are present. Surprisingly little is known about the number of aerobic bacteria which in pure culture can utilise the cellulose or hemicelluloses of plant remains in their natural state, when provided with growth-promoting substances and an organic source of nitrogen. Nearly all the work done has been concentrated on a search for aerobes that can utilise purified filter paper for their energy and ammonium salts for their nitrogen supply, and specialised organisms having these properties can be found in soils and compost heaps. But direct observation of decomposing plant tissue between crossed nicols shows that the individual colonies of bacteria that attack the birefringent cellular fibres also

[1] S. A. Waksman and W. Nissen, *Amer. J. Bot.*, 1932, **19**, 514.
[2] *Ann. Appl. Biol.*, 1945, **32**, 38.
[3] *Symb. Bot. Upsaliens.*, 1944, **8**, No. 2.
[4] *Pedology*, 1945, No. 2, 102.
[5] *Soil Sci.*, 1931, **32**, 97.

attack at the same time the non-birefringent matrix of hemicellulose and pectins in which the fibres are embedded.[1]

The recognised aerobic cellulose-decomposing bacteria[2] belong to the spore formers, the non-spore formers, the Vibrios, the Cytophagas and possibly other members of the Myxobacteria.[3] One of the first species isolated was a Cytophaga, originally called *Spirochaeta cytophaga*, by H. B. Hutchinson and J. Clayton,[4] but now named *Sporocytophaga myxococcoides*,[5] which is extraordinarily specialised in its food requirements, for it can only use cellulose or glucose sterilised by ultrafiltration;[6] but other members of the group can use cellulose and related carbohydrates and other members only related carbohydrates.[7]

Certain members of the soil fauna can digest plant cellulose, and probably also many hemicelluloses, but there is no evidence to suggest any can digest lignin. Termites, for example, are probably more important digesters of cellulose than the micro-organisms in many tropical soils, whilst in temperate soils, though the micro-organisms play the main role, species of nematodes and possibly mites and insects may also be able to feed directly on these polysaccharides. Unfortunately no critical biochemical examination has been made on just what fractions in the ingested food are digested by these saprophytic animals.

The relative importance of these various organisms in different natural environments has not been worked out in any great detail. Fungi typically appear to initiate the attack on freshly incorporated plant debris, but their dominance is often short-lived, and their mycelia form a readily available food supply for many bacteria. They remain dominant under aerobic conditions in acid soils, but are replaced by typical cellulose decomposing myxobacteria and true bacteria in mildly acid and neutral soils.[8] Under anaerobic conditions bacteria are always the dominant decomposers.

The process of the conversion of plant residues into humus is still not understood. As will be pointed out in Chapter 15, humus appears to be built out of two groups of material—oxidised lignin and by-products of the metabolism of the soil organisms. The outstanding feature of humus formation in soils appears to be the importance of the

[1] F. Baker, *Zbl. Bakt.* II, 1933, **88**; with R. Martin, ibid., 1937, **96**, 18; **97**, 201.

[2] For a general summary of these, see H. L. Jensen, *Proc. Linn. Soc., N.S.W.*, 1940, **65**, 543; also A. Kalnins, *Acta Univ. Latvia*, 1930, **11**, 221 (*Roth. Mem.*, Vol. 16); W. H. Fuller and A. G. Norman, *J. Bact.*, 1943, **46**, 273. For a recent review, A. G. Norman and W. H. Fuller, *Adv. Enzymol.*, 1942, **2**, 239.

[3] H. and S. Krzemieniewski, *Bull. Acad. Pol. Sci. et Lettr. B.*, 1927, 11 and 33.

[4] *J. Agric. Sci.*, 1919, **9**, 143.

[5] R. Y. Stanier, *Bact. Rev.*, 1942, **6**, 143, which contains a review of the classification of the Cytophagas. This is not the organism Winogradsky calls *Cytophaga hutchinsoni*.

[6] R. Y. Stanier, *Soil Sci.*, 1942, **53**, 479.

[7] W. H. Fuller and A. G. Norman, *J. Bact.*, 1943, **45**, 565.

[8] H. L. Jensen, *J. Agric. Sci.*, 1931, **21**, 81; C. E. Skinner and E. M. Mellem, *Ecology*, 1944, **25**, 360.

alimentary canals of the soil fauna. W. Kubiena[1] has shown, for example, that in earthworm-free soils, humification appears to be confined to the excrements of the different species of animals present, and when earthworms are present their excrements predominate over that of all others.

The products of microbial metabolism include microbial cell-wall components such as polyuronide gums and other polysaccharides, as well as lignin- and humic-like substances. Many bacteria, including some of the cellulose decomposers, also produce polyuronide gums, particularly if they are working under conditions of limited nitrogen supply;[2] for they may have to attack a large amount of polysaccharide to extract sufficient nitrogen for their growth; and since it is nitrogen and not energy supply that is limiting their growth, they have to excrete energy-rich by-products. Some fungi produce dark-coloured products similar to α-humus (see p. 257) when growing on cellulose and other lignin-free plant products.[3] Some bacteria may also produce such products, both from the easily decomposable components in recently dead plant tissue,[4] and also from the mycelia of the fungi that originate the attack on the more resistant plant remains.[5]

Green Manuring

Plant residues can be applied direct to the soil instead of via the compost or manure heap, and the usual method of doing this is to plough in a growing crop. This method of green manuring can have several effects on the soil, depending on conditions: it may increase the organic matter content of, or the available nitrogen in, the soil; it may reduce the loss of mineral nitrogen by leaching; and it may concentrate nutrients likely to be deficient in the surface soil and leave them there in a readily available form. Green manuring normally cannot confer all these benefits on the soil simultaneously, and it may confer none of them.

Green manuring, when properly used, can either increase the humus content or else the supply of available nitrogen in the soil, but rarely can it do both at the same time, and therein it differs from well-made farmyard manure, for the humus content only appears to be increased

[1] *Ztschr. Weltforstw.*, 1943, **10**, 387; *Bodenk. PflErnähr.*, 1942, **29**, 108.

[2] See, for example, S. Winogradsky, *Ann. Inst. Pasteur*, 1929, **43**, 549; A. G. Norman and W. V. Bartholomew, *Proc. Soil Sci. Soc. Amer.*, 1940, **5**, 242.

[3] H. L. Jensen, *J. Agric. Sci.*, 1931, **21**, 81; L. A. Pinck and F. E. Allison, *Soil Sci.*, 1944, **57**, 155.

[4] M. M. Kononova, *Pedology*, 1943, No. 6, 27; No. 7, 18; 1944, No. 10, 456; with N. P. Belchikova, ibid., 1946, 529.

[5] F. Y. Geltser, *Sovet. Agron.*, 1940, No. 11–12, 22; also see her book *The Significance of Micro-organisms in the Formation of Humus*, Moscow, 1940; J. G. Shrikhande, *Biochem. J.*, 1933, **27**, 1551.

appreciably if material fairly resistant to decomposition is added to the soil, and resistant plant material is typically low in nitrogen; and the available nitrogen supply is only increased if readily decomposable material high in nitrogen, such as young green plants, are decomposing. Thus, the effect of a given crop as a green manure depends on its maturity when ploughed under. Table 52[1] illustrates this point for rye.

TABLE 52

The Effect of the Maturity of Rye on its Composition and Decomposition

(a) The effect on the carbon dioxide and mineral nitrogen produced during decomposition

Fresh material, containing 2 gm. dry matter, added to 100 gm. soil and incubated at 25° to 28° C. for 27 days

Stage of maturity	Moisture content of material	Per cent of dry matter soluble in cold water	Nitrogen content of dry matter	Carbon dioxide evolved, mgm.	Mineral nitrogen liberated (+) or absorbed (−) mgm.
Plants 10–14 in. high . .	80	34	2·5	287	+ 22·2
Just before heads form .	79	23	1·8	280	+ 3·0
Just before flowering leaves and stalks . . .	57	18	1·0	200	− 7·5
Grain in milk stage, leaves and stalks . . .	15	10	0·24	188	− 8·9

(b) The effect of maturity on the disappearance of plant constituents

Stems and leaves, decomposing in sand at 25° to 28° C. on a basis of 100 gm. of dry matter initially.

Stage of maturity	Just before head forms			Plants nearly mature		
	Initial	After 30 days' decomposition	Per cent loss in 30 days	Initial	After 60 days' decomposition	Per cent loss in 60 days
Water insoluble organic matter .	75	20	73	76	44	42
Pentosans . .	20	4	82	20	8	61
Cellulose . .	26	6	77	31	14	56
Lignin . .	12	8	36	17	15	11
Protein insoluble in water . .	8·2	2·5	69	1·8	5·2	gain 187

[1] S. A. Waksman and F. G. Tenney, *Soil Sci.*, 1927, **24**, 317.

Young rye decomposes rapidly with a large production of carbon dioxide, and consequently leaves little residue but much nitrate nitrogen, whilst mature rye decomposes much slower, leaving a large residue and making demands on the soil's supply of available nitrogen.

This conclusion has recently been questioned by F. E. Allison and his co-workers.[1] They concluded that the proportion of carbon added in a green manure crop that gets converted to resistant humic material only depends on the amount of added carbon and not on the stage of maturity of the green crop. On this view immature green manure crops add little carbon to the soil compared with mature crops because of the much smaller weight of carbon they contain when ploughed under. But this conclusion is based on experiments made by adding the green manure to pots containing only 20 lb. of soil and growing five crops of sudan grass or wheat—experiments in which the root residues of the crops per pound of soil would be far higher than in the field—and it was not possible to allow for the contribution made by these resistant root residues to the resistant humic material in the soil. Hence their conclusions may not apply to green manuring in the field.

Green manuring has, in most parts of the world, been applied more successfully to increasing the available nitrogen supply than the humus content of soils. It is, however, only widely practised under certain definite conditions. The crop must be grown as a catch crop between the main cash crops, and consequently the practice is commonly commended in regions where the winters are sufficiently mild and moist to allow the crop to grow during this period. The crop must not compete with the main crops in any way, and in particular not for water, so that this system is not used under dry-farming conditions.

Hence, regions having a long growing season, such as regions with mild winters and with a well distributed rainfall, or else an adequate irrigation system, are well suited to green manure crops. The practice is prevalent in the humid tropics and sub-tropics, and in orchards when the growing season extends into the dormant period of the trees; it is also extensively advocated in the south-eastern states of the U.S.A., where maize and cotton, both summer crops, are the two main cash crops, and where legumes will grow during the winter. Green manure crops can be particularly valuable in saline soils, because in comparison with fallow, they reduce the evaporation from, and hence the salt content in, the surface soil, for they take their water from the subsoil and shade the surface. Further, when they are ploughed in, their residues will help to increase the availability of phosphates and trace elements to the succeeding crop due to the lowering of the soil *p*H

[1] L. A. Pinck, F. E. Allison and V. L. Gaddy, *Proc. Soil Sci. Soc. Amer.*, 1946, **10**, 230; *Soil Sci.*, 1948, **66**, 39; *J. Amer. Soc. Agron.*, 1948, **40**, 237.

brought about by the carbon dioxide produced in the process of decomposition.

Leguminous crops, such as some vetches, peas and clovers, are commonly used for green manuring as they increase the soil's supply of nitrogen. But these crops will normally only make adequate growth and fix enough nitrogen to make their cultivation worth while if the soil contains an adequate supply of calcium, potassium and phosphates. An example of the need for this is given in Table 53,[1] taken from some experiments made on a soil with *p*H 5·5 in Mississippi. In this example 28 and 56 lb. of nitrogen in the green manure gave rather more cotton than 18 and 34 lb. of nitrogen in a mixed fertiliser.

TABLE 53

Influence of Fertilisers for Green Manure Crop on the Yield of Cotton

Experiment at Holly Springs, Mississippi. Winter green manure crop: Hairy Vetch

	Yield of seed cotton lb. per acre	Yield of vetch	
		Dry matter lb. per acre	Nitrogen lb. per acre
(*a*) No green manure before cotton			
Fertiliser applied to cotton:			
300 lb. 6–8–4	1090	—	—
Ditto, plus 100 lb. nitrate of soda	1430	—	—
(*b*) With green manure, but no fertilisers applied to cotton			
Fertiliser applied to vetch:			
None	930	460	17
Phosphate	1160	720	28
Dolomitic limestone	1480	1160	56
Limestone and phosphate	1550	1210	57

The nitrogen liberated during the decomposition of the green manure crop can only benefit the subsequent crop if the latter is sufficiently developed to take up the nitrogen soon after it is released and before the nitrate produced is leached out of the soil; and this period is fairly short, particularly in light soils under warm moist conditions, as the protein of the living green plant decomposes more rapidly than does that in dried or dead plant material. Hence, a long, wet period between the ploughing-in of a green manure crop and the establishment of the following crop, particularly on light soils, can result in much of

[1] C. D. Hoover, *Proc. Soil Sci. Soc. Amer.*, 1942, **7**, 283.

the nitrifiable nitrogen of the green crop being leached out of the soil with the consequence that the following crop obtains little, if any, benefit from the green manure.[1] On the other hand, the main crop should not be sown too soon after the green crop has been turned in, as the period covering the first flush of decomposition is very unfavourable for germination and the growth of very young plants.

Green manures do not usually increase the humus content of the soil, and in this respect differ from farmyard manure. Thus, C. A. Mooers[2] found that in a twenty-year experiment in which cow-peas were grown as an autumn catch crop in a continuous winter wheat experiment, the organic matter content of the soil decreased by 0·11 per cent, or by about a ton an acre over the twenty-year period on the plots in which the cow-peas, yielding about a ton of dry matter per acre, had been ploughed under and increased by about 0·11 per cent on the plots which received 4 tons of farmyard manure, also containing about a ton of dry matter, each year. The 20 tons of cow-pea dry matter, however, reduced the loss of humus from the soil, for the humus content fell by 0·24 per cent on other plots that did not receive either farmyard manure or green manure. Hence, about 20 tons of cow-pea dry matter reduced the humus loss by about 2,600 lb., whilst 20 tons of farmyard manure dry matter reduced it by 7,000 lb.

Green manuring is relatively ineffective for two reasons. In the first place, as already noted, immature green plant tissue decomposes more rapidly, leaving less residue, than farmyard manure. But there is an additional effect, for adding an easily decomposable material to a soil so stimulates the soil organisms that they not only attack the readily decomposable material, but they also decompose in the process some of the more resistant organic matter in the soil. This effect has been unequivocally established by F. E. Broadbent[3] using sudan grass as a green manure whose tissues contained a measureable amount of heavy carbon C^{13} and heavy nitrogen N^{15}. He added some of this material to a soil, incubated it, and determined the amount of carbon dioxide given off and ammonium and nitrate nitrogen liberated, and from the C^{13} and N^{15} contents of these products calculated what fraction of each was derived from the humic matter in the soil. His results are given in Table 54, and further results are quoted on p. 267, which show that the presence of the decomposable sudan grass has caused the rate of production of carbon dioxide from the humic matter in the soil to increase threefold, and of mineral nitrogen twofold. This effect

[1] See E. M. Crowther in *Fifty Years of Field Experiments at the Woburn Experimental Station*, by E. J. Russell and J. A. Voelcker, for a discussion of the causes of the failure of the Woburn Green Manuring Experiment to benefit the soil or the succeeding crop.

[2] *Tennessee Agric. Expt. Sta., Bull.* 135, 1926.

[3] *Proc. Soil Sci. Soc. Amer.*, 1948, **12**, 246.

obviously limits, very seriously, the effectiveness of green manuring as a means of increasing the organic matter content of the soil.

TABLE 54

The Effect of Additions of Decomposable Matter in increasing the Rate of Decomposition of the Soil Humus

Amounts liberated in milligrams

	Soil plus sudan grass	Soil alone		Soil plus sudan grass	Soil alone
Total CO_2 evolved .	283	19	Total mineral nitrogen released .	4·83	1·40
Part derived from sudan grass .	225	—	Part derived from sudan grass .	1·93	—
Part derived from soil . . .	58	19	Part derived from soil . . .	2·89	1·40

Green manure crops can confer other benefits on the land: by growing during wet off-seasons they reduce the loss of nitrogen and other nutrients by leaching; they can often utilise less available forms of phosphate and zinc than the main crop, and, hence, increase the availability of these for the crop; and by decomposing rapidly they liberate large quantities of carbon dioxide in the soil which can increase the availability of phosphates in alkaline calcareous soils. These benefits may be of particular benefit in deciduous orchards, for they have a long dormant season. The practical difficulties in growing these off-season cover crops for green manuring are to get them established without interfering with harvesting or competing with the trees for nutrients before harvest, and to manage them so they are not killed prematurely by the winter sprays and washes used.[1]

Ploughing in a green crop can have another function that has barely been examined yet. It is possible that the best way of ploughing in straw is to under-sow the corn crop with a green manure crop, probably a legume, and under these conditions the benefit conferred by the legume on the succeeding crop appears to be enhanced. F. C. Bauer[2] has given the results of an experiment in Illinois on the three-course rotation, maize-oats-wheat, in which the effect of under-sowing the wheat with sweet clover and returning the straw to the wheat stubble was investigated. The results for the first twelve years of the experiment were:

[1] For an example of their management in English orchards, see W. S. Rogers and Th. Raptopoulos, *J. Pomol.*, 1946, **22**, 92.

[2] *Proc. Soil Sci. Soc. Amer.*, 1942, **7**, 301.

Residue returned to wheat stubble	Yield of maize in bushels per acre		
	No sweet clover	Sweet clover under-sown in wheat	Benefit of sweet clover
None	58	68	10
Wheat straw and maize . .	59	80	21

and they show that under-sowing the wheat with sweet clover benefited the following maize crop, but this benefit was almost doubled if the wheat and maize straw were put on the sweet clover ley, whilst the straw alone had no effect.

It is a common practice for farmers in several parts of the world who crop their land fairly continuously with a corn or maize crop to under-sow the crop with a legume. Thus, wheat growers in Missouri commonly under-sow their wheat with lespedeza, which can be made both to seed itself for the following year and to provide a hay crop; and Iowan farmers often sow sweet clover or vetch in their maize.[1] English corn growers on chalk and light land soils often under-sow their wheat or barley with trefoil, which not only helps to control "take-all" (*Ophiobolus graminis*) in the corn, but also helps to rot down the straw; for these farmers commonly harvest their corn by combine and plough in the straw. The straw is pressed into the trefoil with a ring roll, and wherever it touches the ground it decomposes, hence it can be ploughed under more easily. The trefoil thus not only helps the straw to decompose while on top of the ground, possibly by keeping the soil surface damp, but also supplies nitrogen for its decomposition when it is ploughed under.

Green manuring can take another form in the humid tropics for bush crops such as coffee and tea. Here either the crops may be grown under leguminous shade trees,[2] such as species of *Erythrina* (dadap) and *Albizzia* (sau), for example; or leguminous shrubs, such as species of *Tephrosia*, may be interplanted between the bushes. These trees and shrubs are lopped several times a year and the green loppings spread around the bushes and perhaps worked into the surface soil. By this means 10 tons or more of green material, containing possibly up to 60 lb. of nitrogen per ton and rich in bases,[3] are provided as a green manure or a surface mulch. This helps to keep the surface layers of the soil, which contain most of the feeding roots of these bushes,

[1] I am indebted to Dr. A. G. Norman for this information.

[2] See, for example, C. R. Harler, *The Culture and Marketing of Tea*, Oxford, 1933, for a short description of this practice.

[3] H. E. Macmillan, *Tropical Planting and Gardening*, London, 1935.

well provided with nutrients and in a porous open tilth. However, nitrogen-rich residues spread over the soil surface as a mulch may increase the available nitrogen in the soil less than if they are ploughed in. Thus T. M. McCalla and J. C. Russel found that the nitrate nitrogen content of a soil was about 10 per cent less under a mulch of sweet clover than when it was ploughed in.[1]

The Decomposition of Green Manures under Water-logged Conditions: Paddy Soils

The course of decomposition of plant residues depends on the aeration of the medium in which they are decomposing, and though in temperate agriculture, decomposition usually takes place under aerobic or slightly anaerobic conditions, yet under some tropical conditions, such as in wet rice or paddy fields, decomposition occurs under water-logged or fairly strongly anaerobic conditions. The main effect of restricting the oxygen supply during decomposition is to encourage the production of organic acids, such as lactic, butyric and acetic, and of gases such as methane and hydrogen, which are themselves probably the decomposition products of the volatile acids under anaerobic conditions. The typical nitrogen end-product of anaerobic decomposition is ammonia, though if alternate oxidising and reducing conditions occur, nitrogen may be set free from the reduction of nitrates.

Some results of C. N. Acharya[2] given in Table 55, illustrate the effects of increasingly severe anaerobic conditions on the rotting of rice straw and on the volume of gas produced. In one set of experiments, he allowed rice straw to decompose at 30° C. for six months, and compared the gas production when the decomposition was strictly anaerobic all the time with that when air was admitted either over the top of the rotting material (moderate anaerobic) or bubbled through it for five minutes (mild anaerobic conditions) once a week.

Table 55 shows that increasing the strictness of anaerobic conditions causes the amount of methane given off to increase, of carbon dioxide to decrease, and the hydrogen first to increase and then to decrease, whilst the loss of dry matter and also the disappearance of cellulose, pentosan and lignin is almost unaffected, though losses are higher under aerobic conditions. The table also shows that decreasing the oxygen supply decreases the nitrogen factor, that is, the amount of ammonium nitrogen immobilised: it decreased from 0·54 for aerobic to 0·07 for strict anaerobic conditions.

[1] *J. Amer. Soc. Agric.*, 1948, **40**, 11. See W. A. Albrecht, *Missouri Agric. Expt. Sta., Res. Bull.* 249, 1936, for a similar result with red clover.

[2] *Biochem. J.*, 1935, **29**, 528, 953, 1116, 1459.

TABLE 55

The Quantity and Composition of Gas Evolved during the Anaerobic Rotting of Rice Straw

Temperature of decomposition, 30° C.

Litres of gas evolved per 100 gm. of straw in 6 months

Degree of anaerobicity	Mild	Moderate	Strict
Carbon dioxide	32·5	17·4	10·8
Methane	2·1	6·9	10·6
Hydrogen	0·92	5·6	0·10
Loss of dry matter in grammes . .	34·0	37·0	35·0
Nitrogen factor	0·33	0·26	0·07

The application of these results to the decomposition of green manures in tropical paddy soils is not, however, simple. Paddy soils are water-logged for much of the year but the water should not be stagnant; the soil's permeability should be sufficiently controlled by puddling to allow a slow percolation of water through it, and the land should be adequately drained to let this water get away. W. H. Harrison and P. A. S. Aiyer[1] showed that the principal gas produced in these water-logged soils during the decomposition of green crops was methane with only small amounts of carbon dioxide, hydrogen and perhaps nitrogen, and the gases in the water above the soil are almost entirely oxygen and nitrogen. In the first place, they showed that this difference in composition was due to a film of organisms in the surface layers of the soil. It contained both bacteria that oxidised methane to carbon dioxide and algae that fixed the carbon dioxide photosynthetically and respired oxygen. Hence, the effect of green manuring under these conditions is to produce oxygenated water, which by percolating slowly through the soil keeps the rice roots supplied with oxygen; and this appears to be the principal means by which rice roots obtain their oxygen.

Harrison later[2] put forward an explanation of why the soil gases were so unexpectedly rich in methane and poor in hydrogen and carbon dioxide, for he showed that there were bacteria in the soil that could utilise hydrogen to reduce carbon dioxide: a reaction which supplied the bacteria both with energy and a source of carbon, which removed 1·5 to 3·5 parts of hydrogen for every part of carbon dioxide reduced,

[1] *India Dept. Agric. Mem., Chem. Ser.*, 1913, **3**, 65; 1914, **4**, 1.
[2] *India Dept. Agric. Mem.*, 1920, **5**, 181.

and which might lead to a production of methane. This is a reaction of great importance for the oxygen régime around the rice roots, for it not only reduces the carbon dioxide content around them, which in itself reduces their oxygen needs, but also removes hydrogen in a way that makes a much lower demand on the oxygen in the soil water than would be made by the hydrogen-oxidising bacteria which he and Aiyer[1] showed were present in the soil.

The nitrogen régime in water-logged soils has not been fully worked out. Nitrates are reduced to ammonia and gaseous nitrogen via nitrites, and nitrites themselves may accumulate sufficiently to be toxic to crops; consequently nitrate fertilisers are not used on paddy soils.[2] Most organic nitrogen compounds decompose to yield ammonia, but it is not certain if gaseous nitrogen is ever produced during these decompositions: its production is usually characteristic of systems with a widely fluctuating oxygen supply in which nitrates are produced during the aerobic periods and reduced during the anaerobic. Thus ammonia is the typical form of inorganic nitrogen and the typical by-product of bacterial metabolism under water-logged conditions; consequently, ammonium salts, or organic fertilisers, such as green manures that break down readily to give ammonium salts, are the typical nitrogen fertilisers for these soils. It is possible, however, that if the ammonium concentration reaches too high a level in the soil some may be lost by volatilisation from the soil's surface under tropical conditions.[3]

[1] *India Dept. Agric. Mem., Chem. Ser.*, 1916, **4**, 135. See also S. B. Lee and W. W. Umbreit, *Zbl. Bakt.* II, 1940, **101**, 354.

[2] M. Nagasko, *Bull. Coll. Agric. Tokyo*, 1904, **6**, 285; W. P. Kelley, *Hawaii Agric. Expt. Sta., Bull.* 24, 1911.

[3] A. Sreenivasan and V. Subrahmanyan, *J. Agric. Sci.*, 1935, **25**, 6.

CHAPTER XV

THE COMPOSITION OF THE SOIL ORGANIC MATTER

The Fractionation of the Soil Humus

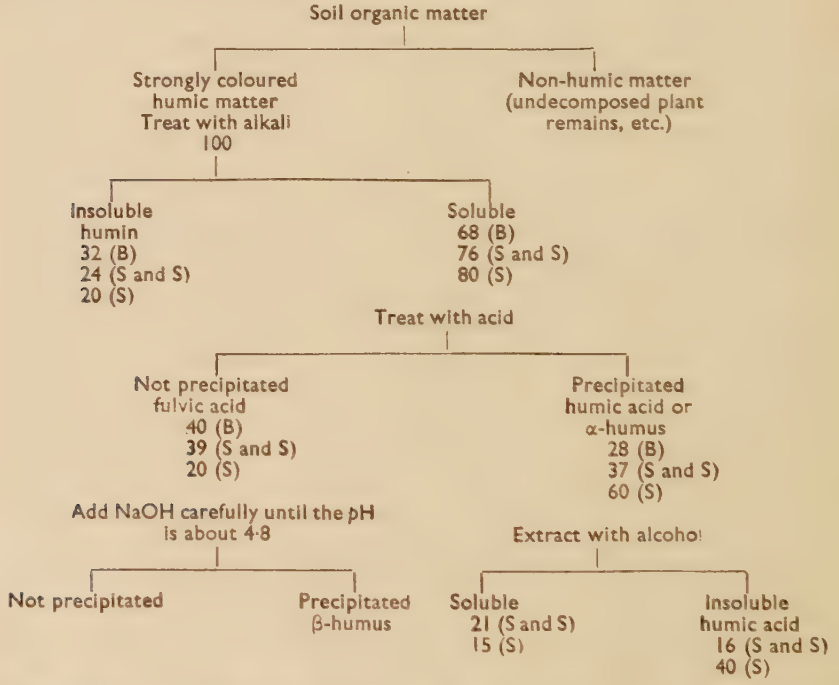
THE COMPOSITION OF the soil organic matter, and in particular of the soil humus, has exercised the minds of soil chemists from the very beginning. The soil organic matter consists of a whole series of products which range from undecayed plant and animal tissues through ephemeral products of decomposition to fairly stable amorphous brown to black material bearing no trace of the anatomical structure of the material from which it was derived; and it is this latter material that is normally defined as the soil humus. The great difficulty in all investigations on the composition of soil humus has been that it cannot all be separated from the unhumified material. The methods used either separate out only certain fractions or else decompose the humus and separate out compounds which are really artefacts and not present in the soil itself.

The early soil chemists were interested in humus. The work was begun by F. K. Achard[1] in 1786 and by C. Vaquelin[2] in 1797, who found that some of it could be extracted by alkali after the soil had first been treated with an acid. The work was continued by C. Sprengel[3] a most successful early investigator in agricultural chemistry, who in 1826 had carried his studies so far that little was added during the next hundred years. He distinguished the "acid humus" of peat found in places where bases are lacking from the less acid "mild humus" formed in soils in presence of basic material; the "acid" is much more stable than the "mild" form, being less easily decomposed to carbon dioxide and water. He prepared "humic acid" by extracting the peat with dilute hydrochloric acid for two hours to remove all bases, washing with water, then extracting with a solution of ammonia in a closed vessel, finally adding to the solution hydrochloric acid to precipitate the humus. It did not, however, come down pure, but contained both clay and ferric hydroxides; it was therefore redissolved in sodium carbonate solution, filtered and precipitated from the filtrate by cold hydrochloric acid.

[1] *Crells Chem. Ann.*, 1786, **2**, 391. For a detailed account of the history of humus chemistry, see the admirable summary of the literature in S. A. Waksman, *Humus*, 2nd ed., London, 1938.
[2] *Ann. Chim.*, 1797, **21**, 39.
[3] *Kastners Arch. ges. Naturlehre* (*Nürnberg*), 1826, **8**, 145.

It was now nearly free from ash constituents: it was black, and when washed free from acid dissolved slightly in water; on electrolysis it travelled to the positive pole, being thus electro-negative like other acids. It formed salts with bases: soluble ones with alkalis, and insoluble ones with alkaline earths and heavy metals. It liberated carbon dioxide from carbonates and silicic acid from soluble silicates; further, it combined with clay and with iron oxide. When dried, it became shiny black, easily pulverised, and highly absorbent of water, but it was now quite insoluble in water. A similar substance was prepared from woody tissues and plant residues by treatment with potassium hydroxide solution in presence of air—the oxygen being supposed to play some part.

The original method of separating the humus from the soil was based on the power of alkalis, and in particular of sodium hydroxide, to disperse much of this organic matter, and the further fractionation of this dispersed sol was effected by partial precipitation with mineral acids and by partial solution in alcohol. The divisions thus made are given in the following diagram:


Soil organic matter
Strongly coloured humic matter Treat with alkali 100
Non-humic matter (undecomposed plant remains, etc.)
Insoluble humin 32 (B) 24 (S and S) 20 (S)
Soluble 68 (B) 76 (S and S) 80 (S)
Treat with acid
Not precipitated fulvic acid 40 (B) 39 (S and S) 20 (S)
Precipitated humic acid or α-humus 28 (B) 37 (S and S) 60 (S)
Add NaOH carefully until the pH is about 4·8
Extract with alcohol
Not precipitated
Precipitated β-humus
Soluble 21 (S and S) 15 (S)
Insoluble humic acid 16 (S and S) 40 (S)

The figures under the fractions show how the carbon is divided among them, as determined by M. Berthelot and G. André (B),[1]

[1] *Ann. Chim. Phys.*, 1892, ser. 6, **25**, 364.

O. Schreiner and E. C. Shorey (S and S)[1] and A. Schmuck (S).[2] These fractions are not, however, pure chemical compounds, and are colloidal sols when dispersed. The following names are still in common use; humin for the fraction insoluble in alkali; humic acid for that soluble in alkali but insoluble in acid; and fulvic acid for that soluble in both alkali and acid. However, humic acid has sometimes been defined as that part of the alkali-soluble acid-insoluble fraction that is insoluble in alcohol. Then the name α-humus has been used for the original fraction.

The German workers[3] have recently been making extensive use of a modification of this scheme, in which the unhumified organic matter is removed from the soil by treating it with acetyl bromide.[4] They consider this reagent only dissolves undecomposed plant material and readily decomposable intermediate products without dissolving any humified material, though it may be necessary to pre-treat the soil with a mineral acid to get some of the plant and insect remains to dissolve in it. The chemistry of the reaction has not been fully established; it is probable that acetyl bromide produces more highly acetylated compounds from undecomposed plant remains than from humified material, and it is these strongly acetylated compounds, rather than the original carbohydrates and lignins, that are dissolved. But this division is arbitrary in that there is no sharp division between unhumified and humified matter, particularly for those materials derived from lignin, and in fact the proportion of the organic matter dissolved can be varied, though usually only within fairly narrow limits, by varying the pre-treatment given to the soil.

Springer also introduced a division of the alkali soluble humus into brown and grey humic acids based on the greater sensitivity of some humic components to flocculation by electrolytes than others. The less sensitive brown humic acids are dispersed in 5 per cent caustic soda solution, which is strong enough to keep the grey humic acids flocculated. They give a brown solution which lightens on standing, and corresponds to Sprengel's acid humus. The grey humic acids which are subsequently dispersed in water appear always to be accompanied by larger quantities of brown, and give grey-brown to black solutions which keep their colour on standing, and this colour can be distinguished chromatographically from the brown without difficulty;[5] it is probably the characteristic component of Sprengel's mild humus.

[1] *U.S. Dept. Agric., Bur. Soils, Bull.* 74, 1910.

[2] *Pedology*, 1930, No. 3, 5.

[3] See, for example, U. Springer, *Ztschr. Pflanz. Düng.*, 1928, A **11**, 313; 1934, A **34**, 1; *Bodenk. PflErnähr.*, 1938, **6**, 312, and a series of papers in *ForschDienst. Sonderh.*, 17, 1941, for a summary of their ideas on this subject.

[4] U. Springer (*Bodenk. PflErnähr.*, 1943, **32**, 129), has suggested a mixture of acetic acid, acetic anhydride and sulphuric acid as a preferable solvent.

[5] A. Hock, *Bodenk. PflErnähr.*, 1937, **5**, 1.

Table 56[1] gives an example of the distribution of these components in the humus of some typical soils.

TABLE 56

The Distribution of the Types of Humus in Different Soil Types

Soil type	Total carbon C_T per cent	Carbon insoluble in acetyl bromide C_H	100 C_H/C_T degree of decomposition	Per cent composition of C_H			$\frac{G}{B+G}$
				Brown humic acids B	Grey humic acids G	Humin	
		per cent					
Podzol	2·5	2·1	86	68	6	24	8
Prairie	6·0	4·6	75	70	19	13	21
Black earth . . .	6·4	4·3	67	46	19	31	21
Chestnut . . .	2·4	1·9	81	72	14	9	16

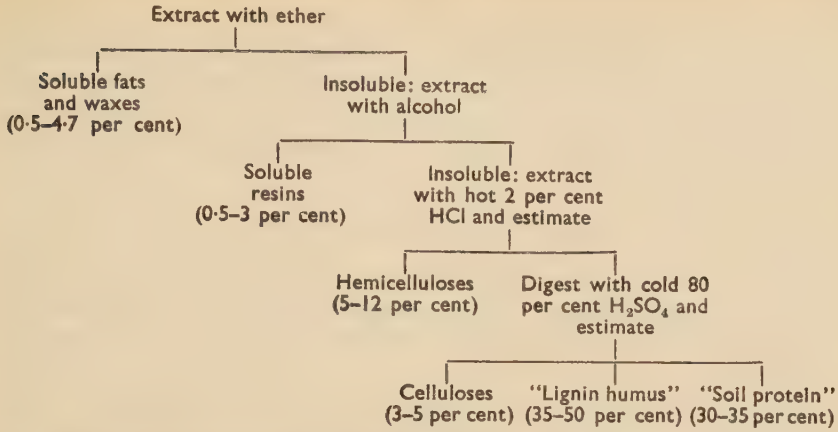
This line of thought has recently been developed into a scheme for dividing the soil organic matter up on the basis of what function it plays in the soil rather than of what it is chemically. Thus the Germans[2] have introduced the concepts of stable humus (*Dauerhumus*) which only decomposes slowly in the soil and corresponds approximately with the acetyl-bromide-insoluble fraction; of nutrient humus (*Nahrhumus*), which decomposes readily and consists of such substances as carbohydrates and proteins, and which corresponds approximately to the fraction soluble in 80 per cent sulphuric acid; and of reserve humus, which is the dead but undecomposed plant and animal remains that will shortly be converted into the other two types.

Another approach to the separation and recognition of the types of material present in the soil organic matter, that has been much used in America, is one developed by Waksman. His method is based on estimating recognisable groups of plant constituents, such as fats, hemicelluloses, and celluloses in the soil organic matter, but he makes no attempt to determine any group of compounds specific to the humic fraction. His scheme of extractions is as shown on the opposite page.[3] He can thus account for about 90 to 95 per cent of the carbon in most soils, but 70 to 80 per cent is in the two large vague groups, soil protein and lignin-humus—the first being obtained by assuming all the nitrogen in the sulphuric acid insoluble organic matter is in the form of protein and the latter by assuming all the residual carbon,

[1] U. Springer, *Bodenk. PflErnähr.*, 1938, **6**, 312.

[2] See, for example, F. Scheffer, *ForschDienst. Sonderh.*, 17, 1941, 14; K. Schmalfuss, ibid., 15.

[3] S. A. Waksman and K. R. Stevens, *Soil Sci.*, 1930, **30**, 97. For results obtained by it see his book, *Humus*, 2nd ed., London, 1938.


Extract with ether
Soluble fats and waxes (0·5–4·7 per cent)
Insoluble: extract with alcohol
Soluble resins (0·5–3 per cent)
Insoluble: extract with hot 2 per cent HCl and estimate
Hemicelluloses (5–12 per cent)
Digest with cold 80 per cent H_2SO_4 and estimate
Celluloses (3–5 per cent)
"Lignin humus" (35–50 per cent)
"Soil protein" (30–35 per cent)

after deducting that needed by the nitrogen to form protein, is lignin or its transformation products. But the groups labelled hemicelluloses and celluloses do not necessarily contain these substances only—at least, not in their simple form—for a considerable proportion of the nitrogen in the soil organic matter may be soluble in the hydrochloric and sulphuric acids.

Still another approach to the fractionation of humic matter in the soil has been made available by an important observation of J. M. Bremner *et al.*[1] They treated soils with neutral solutions of the sodium salts of acids that form co-ordination compounds with calcium and other metallic ions, and found that after this treatment a proportion of the organic matter would disperse in water. The sodium salts of pyrophosphoric, oxalic and citric acids were all about equally efficient, and since the latter two are organic, they are not so suitable as the pyrophosphate. Bremner was later able to show that some of the material dispersed in sodium hydroxide is produced by alkaline hydrolysis of more complex compounds, some of which suffer autoxidation during the process; hence a proportion of the material dispersed in sodium hydroxide is to this extent an artefact.

The various humic fractions obtained by the methods just described are usually mixtures containing polymerised substances, so that they would not be expected to have the same chemical composition when extracted from different soils. Naturally, they are mainly composed of carbon, nitrogen, oxygen and hydrogen, with varying quantities of ash constituents. If the ash content of the organic matter is high, it will principally consist of aluminium and iron oxides and silica; whilst if it is low, the usual ash constituents of plants will be present in about their normal proportions. Ash analysis is not often carried out, as there

[1] *Nature*, 1946, **158**, 790.

are no definitive methods for deciding what part of the ash in a given sample of organic material was a constituent of the organic material, what part was due to any inorganic-organic complexes, and what to contamination of the sample with inorganic soil colloids that had not been properly separated from the organic matter during its preparation.

The Composition and Formation of Humus

The problems of the composition and formation of humus should be distinct, but owing to our very restricted knowledge of its constitution, our theories of its composition are bound up with those of its formation.

The outstanding difference between the carbon compounds in plant residues and in the humic matter of the soil is in the relative importance of cellulose, which is abundant in plant residues, but lacking in well-humified material. However, a proportion of the carbon in most soils appears to be in pentose and hexose units, mainly xylose and glucose, occurring either as hexosans and pentosans or else as polyuronides based on glucuronic acid.[1] But over half the carbon is usually in compounds not based on these units, much of the remainder probably being based on the lignin unit.

The humic matter in the soil appears to be derived from two main sources—the lignins in the plant residues added to the soil, and the products of microbial metabolism, either actual excretions from the living cells, or else structural elements of the cells which are returned to the soil on their decomposition. The relative importance of these two sources are not known, unless the carbon compounds based on the hexose and pentose sugars are all products of microbial metabolism, nor has it yet been rigorously proved that these two sources constitute the predominant part of the humic fractions, though on present evidence this is sufficiently likely to be assumed in this discussion. The lignins alone cannot be the sole source of humic material, for W. Sauerlandt has calculated that in normal arable soils the rate of oxidation of humic matter is greater than the rate at which lignins are added to the soil.

The conversion of lignin to humic matter involves two processes: an oxidation and an enrichment in nitrogen. The oxidation processes can be followed very roughly as their effect is to increase the number of carboxylic acid (—COOH) groups. This oxidation takes place spontaneously in the presence of air in an alkaline medium,[2] and if

[1] W. G. C. Forsyth, *Chem. Indust.*, 1948, 515.

[2] For examples of the uptake of oxygen by lignin and partially humified materials, see E. C. Shorey, *U.S. Dept. Agric., Tech. Bull.* 211, 1930, and E. Juncker, *Kolloid-Ztschr.*, 1941, **95**, 213.

ammonia is also present, some of this is converted into a part of the new oxidised product, though the way the nitrogen is linked in the oxidised product is not known. The effect of this oxidation is that both the base exchange capacity of the material at *p*H 7[1] and the amount of nitrogen fixed from an ammonia solution[2] increase linearly with the amount of oxygen absorbed. Mattson showed that this reaction is not confined to lignin; other polyphenols, such as resorcinol, hydroquinone, gallic and tannic acid react in the same way. Further, W. Laatsch[3] has shown that actinomycetes in particular, but fungi also, produce quinone and related compounds that behave much like lignin to give, on further autoxidation in the presence of amines and amino acids, substances very similar to soil humus, though these conversions were usually done by the micro-organisms in the course of their metabolism. Finally N. H. S. van Reesema[4] has shown that these autoxidised nitrogen-enriched humic-like compounds are very resistant to decomposition in the soil.

It is possible to follow some of the changes that take place as lignin is converted into humic matter. On the one hand, A. G. Norman and his co-workers[5] have shown that the base exchange capacity of lignin increases, and its power of taking oxygen from hypoiodite solution decreases, as the decomposition of the plant material, of which the lignin forms a part, proceeds. On the other hand, the effect of the transformation can be determined from its effect on the number of acetyl ($-CO.CH_3$), methoxyl ($-O.CH_3$) and carboxyl ($-COOH$) groups, on the number of hydroxyl groups that can dissociate hydrogen ions and so act as acids, and on the number of hydroxyl groups that can be acetylated and methylated. Some results of W. S. Gillam[6] illustrate the type of information that can be obtained. He used humic acid, i.e. the alkali-soluble acid-insoluble fraction, in the diagram on p. 256, separated from a prairie, a chernozem and a chestnut soil, analysed them for carbon, hydrogen, nitrogen and oxygen, and determined the number of their acetyl and methoxyl groups, their base exchange capacity up to *p*H 7, and their buffer curves before and after acetylation and methylation. The object of using these two processes is to replace many of the hydroxyl groups by acetyl or methoxyl groups, so preventing them acting as weak acids by dissociating hydrogen ions. The effect of this treatment on the buffer curve of one of his humic acids can be seen in Fig. 20, which is redrawn from his paper. At the same

[1] H. Perrenoud, *Kolloid-Ztschr.*, 1944, **107**, 16; E. Bennett, *Soil Sci.*, 1943, **55**, 427.
[2] S. Mattson and E. K. Andersson, *LantbrHögsk. Ann.*, 1943, **11**, 107.
[3] *Ber. Landtechn.*, 1948, No. 4.
[4] *Landbouwk. Tijdschr.*, 1942, **54**, 119.
[5] With J. B. Bartlett, *Proc. Soil Sci. Soc. Amer.*, 1938, **3**, 210; with W. J. Peevy, *Soil Sci.* 1948, **65**, 209.
[6] *Soil Sci.*, 1940, **49**, 433.

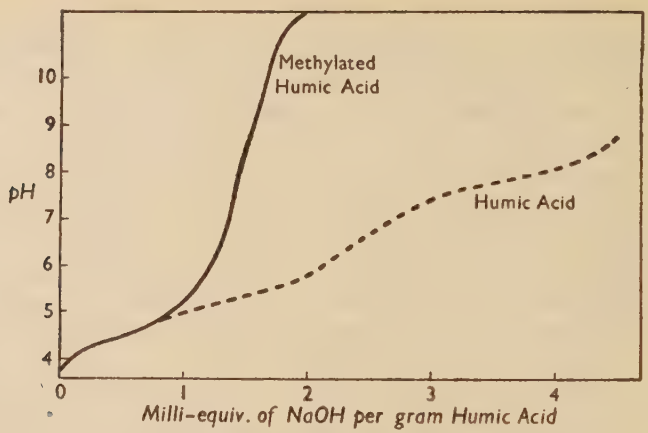


FIG. 20. The effect of methylating humic acid on its titration curve.

time he was able to compare these results with a lignin isolated from a prairie soil and one isolated from corn cobs. Some of his results are given in Table 57.

TABLE 57

Methoxyl Content and Base Exchange Capacity of Humic Acids and Lignins before and after Methylation

In milli-equivalents per 100 gm.

Material	Methoxyl content			Base exchange capacity		
	Untreated	After methylation	Gain	Untreated	After methylation	Loss
Humic acid, P1	33	281	248	394	273	121
P2	54	289	235	274	227	47
P3	56	255	199	253	246	7
Lignin from:						
Prairie soil	56	603	547	339	9	330
Corn cobs	444	935	491	28	2	26

Composition of the Humic Acids

Acid	Separated from	Per cent ash oven-dry basis	Per cent on ash-free basis			
			Carbon	Hydrogen	Nitrogen	Oxygen
P1	Prairie soil	6·9	58·3	4·5	5·9	31·2
P2	Chestnut soil	7·8	58·8	5·5	5·5	30·2
P3	Chernozem soil	3·6	55·6	5·2	6·0	33·2

Clearly, if the humic acid is formed from lignins, its formation involves a gain in carboxylic groups, as shown by the base exchange

capacity that is not neutralised by methylation, though shown equally well by the shape of the buffer curve between *p*H 4 and 5. It also involves a loss of hydroxyls that can be methylated, due, at least in part, to their oxidation to carboxyls and, in the very early stages of the process, a loss of methoxyls.

This work has been extended by W. G. C. Forsyth.[1] He fractionated the humic acid fraction by dilute acid hydrolysis into two parts, which he found were present in roughly equal proportions. The hydrolysable part he considered to be composed primarily of carbohydrates and proteins, and the residual humic acid part carries the organic groups already described. This humic acid can be brought into solution completely by nitration, it is quite insoluble in acetyl bromide, and can be reduced to a pale yellow preparation which darkens again on exposure to air, which suggests that it contains hydroxy-quinone groups. He further showed that methylation, acetylation and esterification did not affect its nitrogen content, which suggests the nitrogen occurs as a constituent part of the molecule. The carbohydrates appear to be merely mixed with the humic acid and not chemically combined with it, for a proportion of them can be removed from the humic acid by solvents such as pyridine.

The fulvic acids, that is, the alkali-soluble acid-soluble fraction of the organic matter, are present in about the same proportion as the humic acid. G. J. Mulder[2] showed they were poorer in carbon but richer in oxygen than humic acid: they contained about 45 per cent of each instead of around the 55 and 35 per cent of humic acid. I. V. Tiurin[3] confirmed these results, though found their exact composition depends on the soil type. He further showed that on acid hydrolysis they yielded 10 per cent of pentosans and 20 per cent uronic acid, yet they have about the same nitrogen content and base exchange capacity as the humic acid.

Recently Forsyth[4] has separated this fraction into four groups, using a selective adsorption technique, and has been able to clarify these findings. One fraction, usually only present in small quantities, contains water-soluble organic compounds such as sugars and amino acids. A second contains phenolic glycosides or tannins. A third is a polyuronide based on glucuronic acid and containing *d*-glucose, *d*-xylose, *l*-rhamnose and another sugar, and seems to have a characteristic composition independent of the soil from which it has been extracted, and is probably of bacterial origin. The fourth fraction is rich in nitrogen, and it contains pentose sugars and organic phosphates.

[1] *J. Agric. Sci.*, 1947, **38**, 132; *Biochem. J.*, 1947, **41**, 176.
[2] *Die Chemie der Ackerkrume*, Berlin, 1861.
[3] *Trans. Dokuchaev Inst.*, 1940, **23**, 23.
[4] *Biochem. J.*, 1947, **41**, 176.

J. M. Bremner,[1] using the much milder neutral pyrophosphate treatment instead of alkali for dispersing the humic and fulvic fractions, found that the pyrophosphate method gave the same general groups of components in the fulvic acid fraction, but their relative proportions appear to depend on the treatment used. Hence his work indicates that at least some of them may be artefacts produced by hydrolysis and other side-reactions of the original humic material in the sodium hydroxide solution used for dispersion.

The third group of substances in the humic matter are the humins which will not disperse in caustic soda. The gross composition of this fraction is intermediate between that of the fulvic and humic acids, and it is possible that part at least may be a polymerisation product of some fulvic with some humic fraction.[2] But they also contain undecomposed or partially decomposed plant and microbial residues, and Forsyth[3] has found that up to 40 per cent of this fraction may be carbohydrates containing glucose, xylose and glucosamine residues.

The conclusions reached from the study of the composition of the various humic fractions can be amplified a little from the results of a few analyses made on the unfractionated organic matter. The two that are most relevant concern the possibility of polyuronides and proteins being present.

E. C. Shorey and J. B. Martin[4] and A. G. Norman and W. V. Bartholomew[5] have both concluded that between 10 and 30 per cent of the organic carbon in the soil is present as polyuronides. Neither group of workers have isolated uronic acids from the soil, but they based their conclusion on the assumption that the carbon dioxide liberated from the organic matter when it is boiled with 12 per cent hydrochloric acid came from the decomposition of the uronic acids, as in our present state of knowledge this is the only probable source of carbon dioxide recognised in the soil.[6] Forsyth's actual isolation of a glucuronic acid polymer from the soil shows that they are present, but it has not yet been proved experimentally that they really are present in the amounts indicated by the carbon dioxide evolution test.

It is possible these polyuronide gums constitute the active humus of Geltser (p. 417), and the humic-like substances that M. M. Kononova[7] working with lucerne roots and W. Sauerlandt[8] with straw found were

[1] Unpublished observations. I am indebted to Mr. J. M. Bremner for allowing me to use these results.

[2] I. V. Tiurin and E. L. Gutkina, *Trans. Dokuchaev Inst.*, 1940, **23**, 41.

[3] *Chem. Indust.*, 1948, 515.

[4] *J. Amer. Chem. Soc.*, 1930, **52**, 4907. See also S. A. Waksman and H. W. Reuszer, *Soil Sci.*, 1932, **33**, 135.

[5] *Soil Sci.*, 1943, **56**, 143.

[6] For further confirmation of the validity of this assumption, see W. H. Fuller *et al.*, *Soil Sci.*, 1947, **64**, 143, 183, and M. V. Tracey, *Biochem. J.*, 1948, **43**, 185.

[7] *Pedology*, 1943, No. 6, 27; No. 7, 18; 1944, No. 10, 456.

[8] *Bodenk. PflErnähr.*, 1944, **35**, 45.

produced in the early stages of the decay of the plant tissues before the lignin had begun to be attacked. However, this is still only surmise, as the chemical composition of these early products of decomposition has not yet been investigated.

The analysis of the nitrogen compounds in the soil has not progressed very far. In most soils only 2 to 3 per cent is in the form of nitrate and ammonia, and the rest is in organic combinations which are very resistant to decomposition. Some of the compounds containing the nitrogen in the soil can be recognised by hydrolysing the soil organic matter with hot mineral acids, such as 20 per cent hydrochloric. By this means R. T. Kojima[1] showed that about one-quarter of the nitrogen is in combinations that are not brought into solution during hydrolysis, about one-third appears as α-amino acids, one-tenth as ammonia, leaving about one-fifth present in solution in other forms, and J. M. Bremner[2] has carried the analysis a little further by showing that at least one third of the nitrogen in the humic acid fraction and one-fifth of that in the fulvic acid is liberated as α-amino acids. The α-amino acids are derived from the hydrolysis of proteins, so that at least one-third of the nitrogen present in the soil is present as protein. Some of the ammonia liberated during the hydrolysis may come from acid amide residues of proteins, such as asparagine and glutamine. If it is assumed that all the ammonia liberated has come from these amides then about half the soil nitrogen would be present as proteins. Kojima[3] has made some estimates of the types of amino acids present in an organic soil and finds that leucine, isoleucine and valine account for about one-third, the hydroxy-carboxylic amino acids about one-fifth, and the di-carboxylic amino acids about one-quarter of the total amino nitrogen. Aspartic, glutamic and probably hydroxyglutamic acids accounted for about one-half of the di-carboxylic amino acids.

The compounds that yield ammonia on acid hydrolysis have not all been identified, but some may be derived from amino sugars in compounds such as mucopolysaccharides.[4] Amino sugars have an amino group attached to the ring in the hexose unit, and the ones that have received most attention are those found in the animal world. These are 2-amino sugars, such as 2-amino glucose (glucosamine) and 2-amino galactose; and chitin, a characteristic polysaccharide of insects and fungi is built out of acetyl glucosamine residues. It has not yet been proved if 2-amino sugars yield ammonia on acid hydrolysis, as those that have been investigated do not, though other amino sugars do.[5] Bremner[6] has shown that both 2-amino sugars and acetylated 2-amino

[1] *Soil Sci.*, 1947, **64**, 157. [2] *J. Agric. Sci.*, 1949, **39**, 183. [3] *Soil Sci.*, 1947, **64**, 245.
[4] I am indebted to Mr. W. N. Pirie for drawing my attention to these substances.
[5] E. Fischer and K. Zach, *Ber. deutsch. chem. Ges.*, 1911, **44**, 132.
[6] I am indebted to Dr. Bremner for these unpublished observations.

sugars not in the form of chitin, are present in the soil. Further evidence is accumulating that many groups of soil micro-organisms produce amino sugars either in gums they secrete or in their cell walls.[1]

All the nitrogen in the fulvic acid, but only about half that in the humic acid fraction, is easily hydrolysable. The nitrogen in the other half of the humic acid fraction, namely, that attached to the lignin nucleus, is in combinations that have not yet been identified; they are not removed by methylation or nitration and are presumably similar to those in which it is held in plant lignins (see p. 231). Mattson has, however, shown that the maximum nitrogen content of the lignin nucleus increases with its degree of oxidation, that is, with the number of carboxyl groups it contains.

One of the fundamental problems in the theory of the composition of soil humus has been to account for the great resistance of the nitrogen compounds to microbial attack; for they were early assumed to be proteins, and recent work has confirmed that at least one-third of the nitrogen is present in this form. Yet all known proteins are readily attacked when added to the soil. Presumably either the soil protein is inaccessible to microbial attack, being protected by a lignified or humified mantle, or else the hydrolysable groups on the protein are so protected. As early as 1892 A. Hebert[2] and P. P. Dehérain[3] had suggested the cause of this stability was that humus is an association between lignin and proteins synthesised by the micro-organisms, and this suggestion was revived independently by H. J. Page and R. P. Hobson[4] and by S. A. Waksman and K. R. N. Iyer.[5] Page and Hobson showed that alkaline lignin solutions can be partially oxidised with ease, and in this state can readily combine with proteins to form stable complexes. Waksman and Iyer suggested the reaction was similar to a tanning process, the hydroxyls of the lignins condensing with the amino groups of the protein, and they showed that such compounds were resistant to further decomposition.

But these theories will not account for the stability of the proteins in the fulvic acid fraction, for this contains no lignins. It is possible that these proteins are held as exchangeable bases on the surface of clay particles, or even perhaps by the carboxyls of the humic acid, for L. E. Ensminger and J. E Gieseking[6] showed that proteins so held were resistant to hydrolysis, presumably because the hydrolysable groups in the protein molecule are oriented towards the charged surface and are

[1] J. P. Martin, *Soil Sci.*, 1946, **61**, 157; W. N. Haworth *et al.*, *Nature*, 1946, **158**, 836. For a list of bacteria producing nitrogen-containing gums, see J. R. Porter, *Bacterial Chemistry and Physiology*, New York, 1946; and for a review of the properties of such gums, see M. Stacey, *Adv. Carbohyd. Chem.*, 1946, **2**, 162.

[2] *Ann. Agron.*, 1892, **18**, 536.

[3] *Traité de Chimie Agricole*, Paris, 1892.

[4] *J. Agric. Sci.*, 1932, **22**, 497.

[5] *Soil Sci.*, 1932, **34**, 43; 1933, **36**, 57.

[6] *Soil Sci.*, 1939, **48**, 467.

attracted so close to it that they are inaccessible to the enzymes excreted by the soil population. But it is still very uncertain if this is an adequate description of why the soil organisms are unable to readily utilise the available energy stored in the soil proteins.

The corresponding problem arises about the uronic acid complexes in the soil, for typical uronides, such as pectin and alginic acid, decompose fairly readily. The answer may lie simply in the constitution of the soil uronic acids, for W. H. Fuller[1] has shown that they are probably by-products of microbial decomposition and have different properties and therefore a different constitution from the plant polyuronides.

The cause of the resistance of the soil organic matter to microbial attack is still very obscure. Recent work of F. E. Broadbent and A. G. Norman[2] using isotopic nitrogen N^{15} and carbon C^{13} compounds, has established the rather unexpected result that merely adding decomposable organic matter to the soil causes a considerable increase in the rate of decomposition of the soil organic matter present, as has already been shown in Table 54 on p. 250. As a further example of their results, in another experiment they added 1 and 2 gm. respectively of sudan grass to 100 gm. of soil, incubated the soil for eleven days and measured the CO_2 produced, and since 2·67 per cent of the carbon in the sudan grass was C^{13}, they could compute the proportion of the CO_2 produced that came from the oxidation of the soil organic matter. They found that 49 mgm. of CO_2 were produced from the organic matter when the soil was incubated by itself, but that 216 and 329 mgm. were produced from it when 1 and 2 gm. of sudan grass were added. At the same time 418 and 651 mgm. of CO_2 were produced from the decomposition of the sudan grass. Thus, for about every 100 mgm. of CO_2 produced from the sudan grass by the soil micro-organisms, an additional 40 mgm. is produced from the soil organic matter. So far no quantitative reasons can be given of why the soil organic matter becomes a better source of food for the soil population in the presence than in the absence of readily decomposable organic matter.

There are many important practical consequences of this result, if it is of general validity. Thus, if the rate of oxidation of straw or similar organic matter in the soil is being limited by lack of nitrogen, adding a nitrogen fertiliser, by increasing the rate of oxidation of the straw, will also increase the rate of oxidation of the organic matter in the soil, and hence also the release of soil nitrogen—a result verified by Broadbent and Norman in laboratory experiments and by H. D. Chapman and G. F. Liebig[3] in the field. Further green manuring,

[1] *Proc. Soil Sci. Soc. Amer.*, 1947, **11**, 280.
[2] *Proc. Soil Sci. Soc. Amer.*, 1947, **11**, 264; 1948, **12**, 246.
[3] *Proc. Soil Sci. Soc. Amer.*, 1947, **11**, 388.

particularly if the green plants turned under are succulent, may actually decrease the humic matter content of the soil, for the flush of decomposition which the green matter will undergo will cause a great increase in the rate of decomposition of the humic material present. This is in accord with observation, for green manuring has often been found to be incapable of maintaining or increasing the organic matter content of the soil, though it may be an excellent way of adding nitrogen compounds to the soil. Further, this additional decomposition brought about by the green manure will release not only carbon dioxide and nitrates, but also phosphates and other minerals locked up in the soil organic matter, and it may be that this phosphate is as important as the phosphate in the green manure itself for the nutrition of the crop.

Two aspects of the present theory of humic acid formation from the oxidation of lignin with the corresponding uptake of ammonia, have not yet been examined in detail. The first concerns the consequences of the lignin oxidation, and the second the place where it occurs. The greater the degree of oxidation the greater the number of carboxylic acid groups formed, and, hence, unless adequate bases are present the acidity of the organic matter will increase. Further, this oxidised material carries a higher negative charge, and hence may be more easily dispersible. There appears to be evidence that these consequences may be of practical importance in the liming of some acid peats, for if an inadequate supply of lime is given it may lead to a lowering of the soil's *p*H and an increase in the rate of leaching of humic materials into the subsoil. Hence, the recommendation that enough lime should be added to ensure that the soil is brought through the range *p*H 4·5–6 as quickly as possible.[1]

Mattson[2] has discussed other consequences of this reaction. Thus chernozem humus, being produced under neutral or slightly alkaline conditions, should be more oxidised and so have a higher base exchange capacity and a higher nitrogen content than podsol humus, which is formed under acid conditions. This is in accord with observation. Thus, A. G. Norman and W. J. Peevy[3] found that the lignin material in prairie soils took up much less oxygen from a hypoiodite solution than that from podsolic soils, a result they could not interpret. Again, M. D. Ridalevskaya and V. V. Tischenko[4] found that at *p*H 7 a podsol humus held about 280 and a chernozem about 490 milli-equivalents

[1] K. Simon and A. Schmidt, *Ernähr. Pfl.*, 1935, **31**, 81; P. Schachtschabel, *ForschDienst. Sonderh.*, 17, 1941, 41.

[2] With E. K. Andersson, *LantbrHögsk. Ann.*, 1943, **11**, 107.

[3] *Proc. Soil Sci. Soc. Amer.*, 1939, **4**, 183.

[4] *Pedology*, 1944, 491. For other figures, see P. Schachtschabel, *Bodenk. PflErnähr.*, 1940, **22-23**, 643; *ForschDienst. Sonderh.*, 17, 1941, 41; Z. Y. Lein, *Trans. Dokuchaev Inst.*, 1940, **23**, 59.

per 100 gm., and M. S. Anderson and H. G. Byers[1] found that the ratio of carbon to nitrogen in the humus of the surface soil of a podsol was about 22, of a podsolic soil about 12·6, of a prairie soil about 12·2 and of a chernozem about 9·0.

Again, it can explain the increase of the nitrogen content of humus down the soil profile, to be discussed on p. 272; for the higher the nitrogen content, the greater the number of acidic groups and the higher the electric charge on the particles, so the more easily they can be dispersed and leached down the profile. This is in agreement with C. W. B. Arnold and H. J. Page's[2] findings that most of the subsoil humus in arable soils has been leached down from the surface and not formed *in situ* from the decomposition of plant roots, and also that a higher proportion of the carbon of the subsoil humus than of the surface is dispersible in cold alkali.

The second important aspect of the theory of humic acid formation by the autoxidation of lignin with the simultaneous fixation of ammonia is the place in the soil where it occurs. Direct experimental proof of where this takes place is lacking, but the observations of foresters, such as P. E. Müller[3] and W. Kubiena, indicate very definitely that the gut of the saprophagous soil animals is a very important site for humus formation, for their faecal pellets contain partially humified plant residues. These pellets remain in the soil for a considerable time if there are no earthworms present, and their shapes are characteristic of the animal—mite, beetle, millepede—that produced them. This humus forms the insect mull of Müller. But in most soils the principal site of lignin oxidation and humus formation may be in the gut of the earthworms where the decomposition of the plant residues takes place in intimate mixture with fine mineral particles in the presence of a good supply of calcium ions. These problems are, however, discussed again in Chapter 30.

Thus, by way of summary, the present ideas on the constitution of soil humus is that it consists of two parts, intimately mixed, but only in part forming co-polymers. One part is derived from lignin by oxidation and ammonia fixation, which may often take place in the gut of the saprophagous soil animals; the other part is composed of pentose and hexose units, partly in the form of uronic and possibly amino-uronic acids, and of proteins, and these are probably derived from the metabolic products or the dead cells of the soil micro-organisms, and not directly from the plant tissues.

[1] *Soil Sci.*, 1934, **38**, 121.
[2] *J. Agric. Sci.*, 1930, **20**, 460.
[3] *Studien über die natürlichen Humusformen*, Berlin, 1887; *Ann. Sci. Agron.*, 1889, **1**, 85.

THE CARBON-NITROGEN RATIO

The carbon-nitrogen ratio of the organic matter has been frequently determined, both because it is not necessary to separate the organic from the mineral matter, and also because many workers have considered such values helpful in assessing the influence of the organic matter on plant growth. The results of this analysis suffer from the serious limitation that they cannot be definitely interpreted, as the carbon compounds present in the soil are very heterogeneous: they vary from plant remains in various stages of decomposition through humified material to charcoal. Yet such is the lack of appropriate methods for analysing the soil organic matter that the ratio of the total carbon in the soil to the total nitrogen gives as useful a characterisation of the properties of the organic matter in the soil as any other method yet in use.[1]

TABLE 58

Distribution of the C/N Ratio in some British and American Soils

	Percentage of soils examined whose C/N ratio falls in the range				
	below 5·5	between 5·5 and 8·4	between 8·5 and 11·4	between 11·5 and 14·4	above 14·4
British	—	6	76	18	—
American:					
Surface	—	11	38	21	30
Sub-surface	4	39	28	15	14
Subsoil	23	56	13	6	2

The carbon-nitrogen ratio of many normal agricultural and natural soils falls within narrow limits, though because of the complications already mentioned, there can be large variations between soils. Table 58 gives an example of this variability for fifty British[2] and sixty-three American[3] soils, which were, however, not selected to show the range of variability that might be expected under extreme conditions. But this variability has often been discounted because in normal fertile arable soils, not containing any pieces of charcoal, as many soils do, the ratio is surprisingly constant and surprisingly independent of soil treatment. Table 59 illustrates this latter point, showing how at Rothamsted very different forms of manuring and cropping have only had a small influence on the C/N ratio, although they have caused large differences in the carbon and nitrogen contents. A C/N ratio of around 10 is, in fact, very common for English arable soils.

[1] For an account of the early literature on C/N ratios, see *Soils and Fert.*, 1945, **8**, 135.
[2] W. McLean, *J. Agric. Sci.*, 1930, **20**, 348.
[3] W. R. Leighty and E. C. Shorey, *Soil Sci.*, 1930, **30**, 257.

TABLE 59

The Carbon and Nitrogen Contents and C/N Ratio of some Rothamsted Soils

	Per cent C	Per cent N	C/N
Old pasture (3–7 in.)[1]	1·52	0·160	9·5
Old woodland (5–7 in.)[1]	2·38	0·250	9·5
Broadbalk, after 50 years' continuous wheat, 1893:			
No manure since 1839 (0–9 in.)	0·89	0·099	9·0
Complete minerals and 412 lb. of sulphate of ammonia most years since 1843 (0–9 in.)	1·10	0·12	9·0
14 tons of farmyard manure annually since 1843 (0–9 in.)	2·23	0·22	10·1

A consequence of this relative constancy of C/N ratio in a soil is that added organic matter decomposes to leave a residue having this C/N ratio. Hence, if organic matter low in nitrogen is added to the soil, the soil population will remove all the available ammonium and nitrates present in the soil to help lower the ratio, whilst if it is high in nitrogen, the decomposition will be releasing ammonium or nitrates into the soil. This is, in fact, the problem discussed on p. 235. But since the soil population attacks the added organic matter to obtain energy from it, and since the consequence of this removal of energy, under aerobic conditions, is the production of carbon dioxide, the total carbon content of the material will be reduced, and if there is no loss of nitrogen, or no production of ammonium or nitrate, the C/N ratio will fall. As a consequence there is no strong connection between the C/N ratio of the added material and the level of inorganic nitrogen in the soil, as has already been indicated on p. 238. But if the added material is fairly easily decomposable, such as plant remains, the process of decomposition, in providing a residual product with a C/N ratio of about 10, will release inorganic nitrogen if the C/N ratio of the added material is under 25 and will remove inorganic nitrogen if it is much above 35 in temperate[2] or 50 in tropical regions.[3] On the other hand, if the added material is already partially decomposed, as occurs in the deposits that accumulate on the surface and in the superficial layers of undisturbed soils, the process of decomposition will involve a smaller release of carbon dioxide per unit of carbon, and hence inorganic

[1] I am indebted to Mr. R. G. Warren for these figures.
[2] L. A. Pinck *et al.*, *J. Amer. Soc. Agron.*, 1946, **38**, 410.
[3] C. N. Acharya *et al.*, *Indian J. Agric. Sci.*, 1946, **16**, 178.

nitrogen may be taken up from the soil if the C/N ratio is considerably smaller than 35.

F. Hardy[1] has recently given an example of the value of a knowledge of this ratio in soils coming under cultivation. He found that in the cotton-growing areas of Queensland and the West Indies, if the C/N ratio of the undisturbed soil was below 8·5 in Queensland or below 10 in the West Indies, cultivation released nitrates from the soil organic matter too rapidly for good cotton production: it is only on soils with a higher C/N ratio that good cotton is being grown.

Certain general relations seem to hold between the carbon and nitrogen contents of a soil and the external conditions. The C/N ratio is typically higher under acid than neutral conditions, as would be predicted from Mattson's theory of humic acid formation that the nitrogen content of this fraction increases with its degree of oxidation, which in turn increases with the *p*H of the soil in which it is being formed. Thus low-moor peats or fens and chernozems, formed in the presence of an adequate lime and mineral supply, typically have a higher nitrogen content, and hence a lower C/N ratio, than high-moor peats and podsols formed under acid conditions. H. Hesselman[2] found the nitrogen content of forest humus tends to increase with increasing *p*H, and B. D. Wilson and E. V. Staker[3] found a very definite correlation between the C/N ratio of some New York peats and their calcium contents; in fact, their data show that the C/N ratio is more closely related to the calcium content than to the *p*H of the peat. Again, any conditions that encourage decomposition usually lower the C/N ratio, for the main effect of a rapid decomposition is for much of the carbon to go off as CO_2, leaving the nitrogen in the soil. Thus, cultivating a forest soil typically lowers the C/N ratio, and the C/N ratio of grassland soils under similar conditions of humidity tends to decrease as the mean annual temperature increases,[4] i.e. as the mean rate of decomposition increases.

The constitution of the soil organic matter must also vary down the soil profile, for the C/N ratio decreases with depth and may reach figures as low as 4 under some conditions.[5] An example of this is given in Fig. 21, which shows the fall in the carbon content and C/N ratio down the Rothamsted profile. These nitrogen-rich compounds have not yet been investigated, but their nitrogen content is approaching that of a protein and is similar to that of bacterial protoplasm.

[1] *Trop. Agric. Trin.*, 1945, **22**, 119; 1946, **23**, 178.
[2] *Medd. Skogsförsöksanst*, 1926, **22**, 169.
[3] *Cornell Agric. Exp. Stat., Bull.* 537, 1932.
[4] H. Jenny, *Missouri Agric. Expt. Sta., Res. Bull.* 152, 1930.
[5] For an example from Scottish forest soils, see J. M. Shewan, *J. Agric. Sci.*, 1938, **28**, 324.

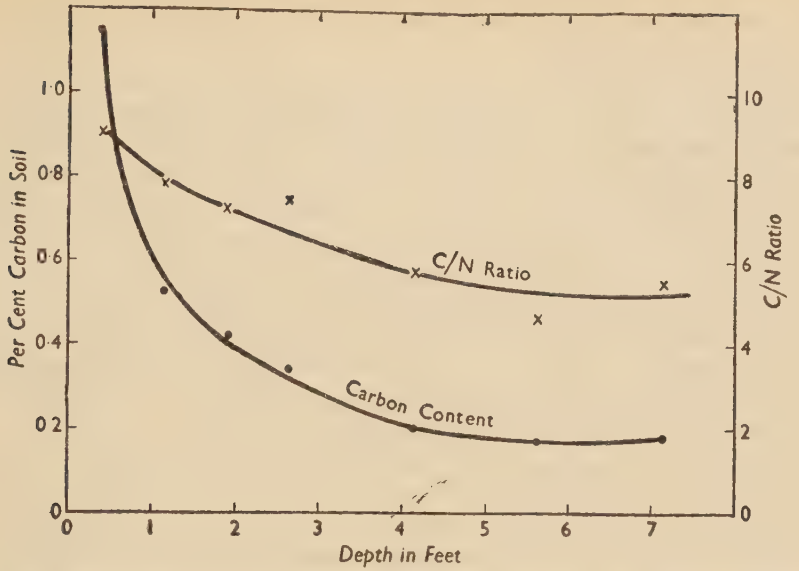


FIG. 21. The percentage of carbon and the C/N ratio in the first 7 feet of Broadbalk soil.[1]

The Phosphorus Compounds in the Organic Matter

All soil organic matter contains phosphorus, derived in the first instance from the plant residues returned to the soil. There is not much data on the phosphorus content of organic matter because of the great difficulty of bringing all the organic phosphorus into solution or suspension without breaking it down to inorganic phosphates. Some results of R. W. Pearson and R. W. Simonson[2] for seven Iowa soils indicate that the carbon-phosphorus ratio in the organic matter commonly lies between 100 and 200 and the nitrogen-phosphorus ratio between 8 and 16, though some of their results fell considerably below these limits.

The principal organic phosphorus compounds in the soil may not yet have all been recognised. Phytin, which is inositol hexaphosphate, and other inositol phosphates certainly occur. C. A. Bower,[3] working in Iowa, found that about 40–50 per cent of the organic phosphorus could be hydrolysed to inositol phosphates, of which about two-thirds was phytin and one-third mainly the triphosphate. W. J. Dyer and C. L. Wrenshall[4] also found phytin was present in considerable amounts in a Canadian peat, though R. K. Yoshida's[5] results on some Hawaiian soils

[1] B. Dyer, *U.S. Dept. Agric., Office Exp. Sta., Bull.* 106, 1902.
[2] *Proc. Soil Sci. Soc. Amer.*, 1939, **4**, 162. J. T. Auten (*Soil Sci.*, 1922, **13**, 119), also of Iowa, found similar ratios.
[3] *Soil Sci.*, 1945, **59**, 277. [4] *Soil Sci.*, 1941, **51**, 235. [5] *Soil Sci.*, 1940, **50**, 81.

indicate that a much smaller preparation of their organic phosphates is combined with inositol.

The second group of phosphorus compounds recognised in the soil organic matter consists of nucleic acid and its nucleotides. Unfortunately it has not yet been possible either to estimate the proportion of organic phosphorus in these compounds, or even to recognise the principal nucleotides present. Thus it is still impossible to say if these two groups—the inositol phosphates and the nucleotides—contain the bulk of the organic phosphorus compounds present in most arable and grassland soils. No other compounds have been recognised in appreciable amounts though small quantities of the phospholipid lecithin have been isolated. Further solutions can be obtained from soil organic matter containing phosphorus in as yet unidentified compounds, though the proportion of phosphorus in these solutions is small.

It is not known in what form the phytin and nucleic acid occur in the organic matter, though presumably most of the nucleic acid must be in nucleoproteins, nor in which humic fractions they are concentrated. They must be protected in some way from the soil enzymes as they are readily dephosphorylated if mixed with the soil, that is, they have their phosphate groups split off as inorganic orthophosphate anions.[1] This is also shown independently by the fact that these organic phosphates can only be extracted in good yield from the humic material if it is subjected to fairly drastic pre-treatment. However, Dyer and Wrenshall[2] found that iron phytate, which they consider to be the principal phytin compound present in acid soils, is much more resistant to dephosphorylation than the free phytin, and C. A. Bower[3] found that nucleic acid and nucleoproteins are strongly adsorbed by montmorillonite clays, and when so absorbed are also much more resistant to dephosphorylation.

The Sulphur Compounds in the Organic Matter

Very little is known about the sulphur content of organic matter or the forms in which it occurs. C. A. Evans and C. O. Rost[4] found that the sulphur content of the Minnesota soils they examined varied from about one-hundredth of the carbon content in the prairie soils to between one-half and one-quarter of this proportion in the podsolic soils. P. Madonov[5] found that the nitrogen-sulphur ratio in the organic matter of some Kazan chernozem and chestnut soils was between 10·5 and 11.4, agreeing fairly well with the ratio of 8–10 found by Evans and Rost for the Minnesota chernozems. Thus it appears as if the sulphur

[1] W. J. Dyer and C. L. Wrenshall, *Soil Sci.*, 1941, **51**, 159; H. T. Rogers, ibid., 1942, **54**, 439.
[2] *Soil Sci.*, 1941, **51**, 235.
[3] *Iowa Agric. Expt. Sta., Res. Bull.* 362, 1949.
[4] *Soil Sci.*, 1945, **59**, 125.
[5] *Pedology*, 1946, 517.

and the phosphorus contents of organic matter are of the same order of magnitude.

Some of the sulphur presumably occurs as the amino acids cystine and cysteine, which in turn are present in proteins derived from plant residues, though these amino acids do not seem to have been isolated from humic material. If these are the principal carriers of organic sulphur they must be present in proteins resistant to hydrolysis.

The Properties of Soil Humus

The properties of the humified organic matter in the soil cannot be directly determined in the same way as those of clays, as there are no gentle ways of separating it from the mineral particles on the one hand or the unhumified material on the other. Nor have any attempts yet been made to compare the properties of the same mineral soil differently treated to produce soils of widely varying humus content and then to estimate the effect of the different amounts of the various humic fractions on the soil properties.

The methods usually adopted to determine the properties of organic matter in soils are to compare the properties either of a range of soils having varied humus and clay contents, though the clay must all be of the same mineralogical composition, or of a series of soils before and after much of their humic material has been removed, as for example by boiling with hydrogen peroxide.[1] Further, it is possible that different constituents can be removed in turn by varying the strength of the peroxide.[2]

Soil humus displays the typical properties of hydrophilic colloids: it can absorb considerable quantities of water and so increase the water-holding power of the soil, it can take part in base exchange reactions, and it can be dispersed and flocculated, so can play an important role in crumb formation. It can also act as an oxidation-reduction as well as an acid-base buffer. Further, it appears to be amorphous, for the only lines that X-ray photographs of carefully prepared humus preparations show are due to small amounts of graphite that the humus sometimes contains.[3]

THE ACID PROPERTIES AND THE BASE EXCHANGE CAPACITY OF HUMUS

Humic acids separated from the soil, or soils poor in inorganic

[1] For examples of these methods, see J. R. H. Coutts, *J. Agric. Sci.*, 1929, **19**, 325; E. W. Russell, ibid., 1933, **23**, 261.

[2] See, for example, W. McLean, *J. Agric. Sci.*, 1931, **21**, 251.

[3] See, for example, E. Jung, *Bodenk. PflErnähr.*, 1946, **37**, 2; N. I. Gorbunov, *Pedology*, 1947, 240.

constituents but rich in humified material, act as strong acids after all the base has been removed. Their acidic properties are due to hydrogen ions dissociating from carboxylic acid groups having a *p*K near *p*H 4·6 under acid conditions, and from various hydroxyl groups under slightly acid or alkaline conditions, as already described on p. 261. No systematic examination has yet been made on the relative importance of these various acidic groups in different types of soil, or on how far they can be altered by varying the soil conditions. Humic material thus differs fundamentally from clay, for it is true acid forming true salts, whilst clay particles merely possess a net negative charge which has to be neutralised by cations.

The acidic property of soil humus that has been most examined is its base exchange capacity as determined by some arbitrary method. At one time it was considered to have a definite value for most soils; thus W. T. McGeorge[1] and P. E. Turner[2] obtained mean values for it from determinations of the loss of exchange capacity and of organic carbon when a range of soils were treated with hydrogen peroxide. But their figures ranged from 150 to 250 milli-equivalents per 100 gm. of humus (assumed to be 58 per cent carbon), and L. C. Olson and R. H. Bray,[3] using a similar method on other American soils, found it varied from 30 to 280 milli-equivalents. This scatter in the exchange capacity of the humus has, in fact, already been discussed on p. 268, for it depends on its degree of oxidation, which in turn depends on the *p*H conditions under which it has been formed.

Typical humic acids of low ash content do not display any noticeable amphoteric properties, hence cannot possess any appreciable number of dissociable basic groups, such as amino groups. But some humic preparations, particularly those containing iron or aluminium compounds, may contain enough basic groups to be amphoteric[4] and to possess one, or sometimes two, isoelectric points. These properties are, however, due to the iron or aluminium present and not to any functional basic organic groups.

The soil humus may also act as an oxidation-reduction system, and in so doing will have its buffering power affected. Mattson[5] has shown that soil humus can take up oxygen from the air, and Norman[6] that it can give up oxygen to hypoiodites; as a consequence during oxidation it becomes more acidic and takes up bases, and during reduction less acidic and gives them up.

[1] *Arizona Agric. Expt. Sta., Tech. Bull.* 30, 1930.
[2] *J. Agric. Sci.*, 1932, **22**, 72.
[3] *Soil Sci.*, 1938, **45**, 483.
[4] See, for example, S. Mattson, *LantbrHögsk. Ann.*, 1935, **2**, 115; 1939, **7**, 63.
[5] *LantbrHögsk. Ann.*, 1943, **11**, 135.
[6] *Soil Sci.*, 1943, **56**, 223.

Clay-Humus Complexes

Humic material has for a long time been known to absorb, or be absorbed by, clay particles. Thus, Th. Schloesing[1] wrote in 1874 that "L'argile possède une certaine tendance a s'unir aux humates du terreau pour former probablement une de ces combinaisions entre colloides signalées par Graham". He attempted to separate the humus from the clay by suspending the mixed sol in ammonia and then adding ammonium chloride which flocculated the clay, but left much of the humus in suspension. He also found that the quantity of chloride required to flocculate the clay increased with the amount of humus present, a phenomenon that was first investigated in any detail by E. Fickendey.[2] Very little is yet known about this combination of clay with humic material. Thus, the humic fractions that take part in this combination have not yet been identified, and until this has been done, all discussions about clay-humus complexes must necessarily be vague.

The structure of the mixed clay-humus suspensions have been investigated by various methods. Thus, H. E. Myers,[3] using viscosometric methods, and D. I. Sideri,[4] using optical methods, have concluded that the absorption of humus by the clay induces the formation of mixed clay-humus micelles in which the majority of the clay particles possess a fairly definite orientation. There is no evidence that the organic colloids ever enter into the crystal lattice of the inorganic colloids; in fact, I. D. Sedletsky and L. Tatarinova[5] found the electron diffraction pattern of the clay-humus complex only possessed the unaltered lines of the clay. But the two colloids can form mixed micelles, which on drying give mixed micro-aggregates of clay and humus.

The evidence for the existence of clay-humus complexes in natural soil is mainly based on the properties of the different colloidal sols that can be dispersed from soils by suitable treatment. When a colloidal suspension is obtained from a soil by treating it with a gentle deflocculating agent, as, for example, by leaching it with sodium chloride and then shaking in water, or by shaking it in a dilute sodium hydroxide solution, the suspended particles with settling velocities corresponding to coarse clay and fine silt have appreciable amounts of organic matter absorbed on them which cannot be removed by any method of partial flocculation yet tried. But it is not yet known if these particles consist of single grains of coarse clay and fine silt coated with a layer of humic

[1] *C.R.*, 1874, **78**, 1276. [2] *J. Landw.*, 1906, **54**, 343. [3] *Soil Sci.*, 1937, **44**, 331.
[4] *Soil Sci.*, 1936, **42**, 461; 1938, **46**, 267; *Pedology*, 1946, p. 39.
[5] *Pedology*, 1941, No. 9, 33.

matter, or whether they are aggregates or granules of fine clay and humic particles mixed together.

A. T. Tiulin[1] has developed a method for fractionating the clay-humus colloids from a soil by using methods of partial dispersion and flocculation. He considers there are two main types of dispersible soil colloids: one which disperses readily when all its exchangeable ions are sodium and the other which needs a more powerful method. In his early work he referred to the first group as electro-negative, because they could easily be made to acquire sufficient negative charge to disperse, and to the second as amphoteric, because they needed to be treated with sodium hydroxide before they could acquire sufficient charge to disperse. But he later realised that the particles in the second group are not amphoteric: they are merely more firmly aggregated together, hence can only be dispersed by more vigorous means, as, for example, by boiling in water.

Tiulin obtained his first group of particles by leaching the soil with sodium chloride, to replace all the exchangeable ions with sodium, and then dispersing it in water. He found that some of these particles held some humic matter sufficiently loosely for it to be removed from their surfaces when they were redispersed in sodium hydroxide. On adding an adequate amount of potassium chloride the mineral particles with their closely bound humic matter were flocculated and the dispersed humic matter remained in suspension. He considered these flocculated particles are the stable kernel of the clay-humus complex and they contain between 2 and 6 per cent of carbon, depending on the soil conditions.[2] The second group of particles, which required a more vigorous method of dispersion to bring them into suspension, differ from the first in containing about double the amount of humic matter per unit weight of clay and three or more times the amount of iron soluble in such solvents as Tamm's acid oxalate. It would be very interesting to test the effect on the humic matter content of these groups of dispersed clay particles by treating the soil with a pyrophosphate solution, for this removes the metals such as calcium which prevent a part of the humic material from dispersing in water (p. 259).

The value of this method of fractionation has not yet been established, and, in fact, H. J. Atkinson of the Canadian Department of Agriculture seems to have been the only worker outside Russia who has used this method. His results[3] confirm those of Tiulin; thus they both find that the group I colloids are the main carriers of the available nitrogen and phosphates in the soil; that the fertility of a soil increases with the

[1] *Soil Sci.*, 1938, **45**, 343; and for his recent modification of technique, see *Lenin Acad. Agric. Sci.*, No. 27, 1946.
[2] M. A. Vinogradov, *Pedology*, 1942, Nos. 3–4, 79.
[3] H. J. Atkinson and R. C. Turner, *Soil Sci.*, 1944, **57**, 233, 243; **58**, 79.

proportion of group I colloids it contains; and that the proportion of group I to group II colloids is higher in chernozems than in podsols. A comparison of some of their results is given in Table 60.

TABLE 60

Ratio of Tiulin's Group I and Group II Colloids in Soils

	Amount of colloid as per cent of air-dry soil		Ratio Group I/II
	Group I	Group II	
Podsols:			
Russian[1]	7·1	12·1	0·59
Canadian[2] (Podsolised) . . .	4·6	6·0	0·77
Chernozems:			
Russian[1]	46·3	18·7	2·47
Canadian[2] High fertility . . .	22·5	12·8	1·75
Low fertility . . .	14·5	15·5	0·94

The present picture of the clay-humus complex is still very indefinite. There are possibly only two types in the soil, one of which the clay and humus particles are held together by calcium ions, the other in which iron in particular, and possibly also manganese and aluminium, can replace calcium, though aluminium has not yet been shown to be able to replace iron in this mechanism. Now that the technique of dispersing metallo-organic complexes with pyrophosphates and other neutral solutions has been developed, it should be possible with its aid to test how far these metallic ions are in fact responsible for binding the humic to the mineral particles. Tiulin's group II colloids probably furnish an example of iron acting as a cement holding clay and humic particles together; and iron, and possibly also aluminium, may be responsible for the binding of the humus particles to the sand particles in the B horizon of a podsol, for the organic matter dispersed from this horizon is rich in iron and possibly also in aluminium, and is in fact the β-humus of Waksman (see p. 256). These complexes, when dispersed in acid solutions, may become positively charged, that is, act as cations and move towards the cathode during the electrodialysis of soils,[3] but they are not considered to confer a favourable structure on the soil.

The clay-humus complex held together by calcium ions is probably

[1] *Soil Sci.*, 1938, **45**, 347. [2] *Soil Sci.*, 1944, **57**, 237.

[3] See, for example, B. D. Wilson and E. V. Staker, *Soil Sci.*, 1937, **43**, 247; A. L. Prince and S. J. Toth, ibid., 1937, **43**, 203.

agriculturally much the most important type and probably includes Tiulin's group I colloids. This complex is supposed to be largely responsible for the favourable physical conditions found in chernozems, composts and wormcasts. Little is known about the structure of this complex. The clay must have an appreciable base exchange capacity; Springer's grey humic acids appear to be the type of humus required, though the essential properties needed for this formation are not known; an adequate supply of calcium must be present, though possibly only to ensure that the correct type of humus is formed; and the alimentary canal of the earthworm is a favourable environment for its formation, but whether this is due to any specific organic excretions or simply because it ensures a thorough mixing of the humus and clay particles in the presence of available calcium is still undecided.

There is little experimental evidence available on how far the proportion of the soil's organic matter in this combination can be increased. On sandy soils additions of clay may be as important as organic matter; and it is possible that a given quantity of a bulky organic manure can only be converted into the maximum quantity of this type of complex if it is composted with a montmorillonite type of clay before being applied to the soil.[1]

There is a third organic-inorganic colloid possible, which can be prepared in the laboratory, but which has not yet been recognised in the field. L. E. Ensminger and J. E. Gieseking[2] found that proteins can be strongly adsorbed by bentonites through their basic groups acting as an exchangeable base, and that this process of adsorption renders the protein more resistant to proteolytic enzymes. However, so little is known about the proteins present in the soil organic matter that no theories about the form they occur in and the reasons for their stability against decomposition can yet be considered properly tested by experiment (see p. 265).

The Level of Organic Matter in Soils

The carbon compounds in the soil are in a continuous flux: carbonaceous plant residues are continually being added which, by forming the primary food supply of the soil population, suffer a series of decompositions and syntheses. Part of the added carbon is converted into living protoplasm, part into the products of excretion of living organisms and part into forms resistant to decomposition. The main loss of carbon from a soil occurs as carbon dioxide diffusing into the

[1] Stated by F. Scheffer (*ForschDienst. Sonderh.*, 17, 1941, 9). O. Siegel and L. Meyer (*Bodenk. PflErnähr.*, 1938, **7**, 190) appear to have first suggested this method, but unfortunately neither they nor any of the other German advocates seem to have given any field evidence for the benefit of this composting.

[2] *Soil Sci.*, 1939, **48**, 467.

atmosphere or being leached out as carbonic acid or bicarbonate, but some loss may also occur under very acid conditions when mobile organic compounds are formed and leached out of the surface layer. They are typically precipitated in the B horizon in the subsoil, though some are washed out, as the colour of rivers flowing through the pine forests of northern Europe clearly shows.

The proportion of carbon in these various forms, and the rate of loss of carbon from the soil, depends on the soil conditions; and if these conditions remain fairly constant the organic matter also remains fairly constant, both in amount and composition; but if any important change takes place—such as a change in the plant association, or in the aeration or drainage of the soil—this equilibrium is upset.

The organic matter content of a soil increases with the rate at which plant remains are added to the soil, though it also depends on the way they are incorporated with it. Forest soils typically have the bulk of their organic matter close to the soil surface, for the forest litter all falls on the surface, and most of the ephemeral tree roots are concentrated near the surface, so that organic matter can only be brought into the sub-surface layer by worms and other soil animals. Prairie soils, by contrast, have a considerable proportion of their organic matter in the deeper horizons, for not only do they receive grass and other debris on their surface, but many of their grasses produce a deep extensive root system which annually may add a greater weight of organic matter to the body of the soil than the leaves add to the surface.[1] The humus, which the decomposition of these roots yield, is thus produced in the deeper layers of the soil. Plate XXVII illustrates this difference for a prairie and a forest soil in Iowa.

Arable soils receive organic matter from the residues of the crops growing on them. The crop always leaves behind much of its root system in the soil, but except for some grass and leguminous leys, the actual weight of roots is usually very small[2] (p. 431). Most crops also leave a stubble and dead leaves, and the larger the crop the greater the weight of these residues, but the main source of organic matter in well-farmed arable soils that carry no leys is the farmyard manure they are given.

The rate of decomposition of the organic matter depends on the soil aeration, calcium supply and temperature. The more favourable a soil is for animal life, by being well aerated and adequately supplied with calcium, the more rapid in general is the decomposition: poorly

[1] J. Kramer and J. E. Weaver, *Univ. Nebraska Conserv. and Surv. Div., Bull.* 12, 1936, quoted by H. Jenny, *Factors in Soil Formation*, New York, 1941.

[2] C. W. B. Arnold and H. J. Page (*J. Agric. Sci.*, 1930, **20**, 460) came to this conclusion for wheat and mangolds, and F. Hardy (*Trop. Agric. Trin.*, 1944, **21**, 203) showed this also held for sugar-cane.

drained or very acid soils which can only carry a small animal population nearly always have a higher organic matter content in their surface layers than well-drained neutral soils. High temperatures also encourage high rates of decomposition; the soil micro-organisms certainly decompose organic matter more vigorously at higher temperatures, though it has not yet been established if this is also true for the soil animals.

The net effect of climate on the processes of addition and decomposition of the soil organic matter for well-drained pasture soils[1] in the U.S.A. is that the organic matter content increases with increasing rainfall and with decreasing temperature—with the former because increasing rainfall favours greater plant growth without having much effect on the rate of decomposition, and with the latter because decreasing temperature both slows down the decomposition processes more rapidly than the growth of the plant, and also because it favours the synthesis of microbial protoplasm (p. 234). Shading the surface of the soil will also increase its organic matter content, for this lowers the maximum soil temperature, and in consequence the rate of oxidation of the organic matter. This effect of shading is seen most strikingly in the tropics, for not only is the difference in day temperature between a bare moist soil, and the same soil under a forest or bush cover appreciable, but oxidation proceeds correspondingly much more rapidly at the higher temperature.

The effect of ploughing out and cultivating a pasture or prairie soil is to reduce its organic matter content, both because the better aeration produced by the cultivations increases the rate of oxidation of the organic matter, and also because of the lower additions of plant remains that usually accompany arable farming. An extreme example of this effect is furnished by peat and fen soils. These soils have accumulated large quantities of organic matter due to them being so badly aerated through water-logging that its decomposition has been inhibited. Draining and cultivating these soils immediately improves the aeration in the soil itself, with the consequence that the organic matter begins to oxidise away and the surface level of the soil sinks; a rate of sinking of 1 to 3 cm. a year is not abnormal. This sinking of the soil surface causes very great complications in the management of the area, for the drainage system must continually be deepened, and the cost of removing the water from the drains will continually rise. O. Djurle[2] has given an example from Sweden, showing how this subsidence can be reduced by keeping the land in grazing leys or pasture as much as possible.

[1] For a discussion of the effect of climate on these soils, see H. Jenny, *Factors of Soil Formation.*
[2] *Svenska Vall-o. MosskFören. Kvartalsskr.*, 1946, **8**, 248.

American experience has consistently shown that the soil organic matter content decreases much faster when the land is cropped to wide-spaced crops, such as maize, which receive considerable inter-row cultivation, than to close-spaced crops, such as wheat, which receive none. Hence, a good crop rotation can have the valuable function of conserving the soil organic matter, as is shown by some results,[1] obtained at the Ohio Experiment Station at Wooster, given in Table 61. Whereas nearly two-thirds of the organic matter has been lost from the continuous maize plots, only about one-sixth has been lost from the three-course rotation.

TABLE 61

Effect of Crop Rotation on the Organic Matter Content of Arable Soils

Crops grown since 1894 without manure or fertiliser[2]
Weight per acre in top 6⅔ inches of soil

	Carbon in 1,000 lb.	Nitrogen in 100 lb.
Initially (1894)	20·4	21·8
After 30 years' cropping to continuous maize .	7·4	8·4
After 30 years' cropping to continuous wheat .	12·8	13·1
Five-course rotation: maize-oats-wheat-clover-timothy . . .	15·5	15·5
Three-course rotation[3] maize-wheat-clover	17·1	17·8

These results show that the organic matter content of an arable soil tends to an equilibrium value depending on the crop rotation practised: for a given soil under given climatic conditions, it is lowest for rotations containing a high proportion of wide-spaced intertilled crops or cultivated fallows, and it increases as the proportion of small grains in the rotation increase, and it increases still more as the proportion of grass leys increase. Fig. 24 on p. 303 shows that this is so for grassland at Rothamsted. The normal nitrogen content of Rothamsted arable land is about 0·11 per cent, and for old grassland 0·25 per cent: when land is laid down to grass its nitrogen content increases rapidly at first, and then slowly up to this figure. Again, when grassland or prairie is broken up for arable the organic matter and nitrogen content fall

[1] R. M. Salter and T. C. Green, *J. Amer. Soc. Agron.*, 1933, **25**, 622. H. E. Myers *et al.*, *Kansas Agric. Expt. Sta., Tech. Bull.* 56, 1943, have given another good example of these effects in that State.

[2] Some plots received dressings of lime, which appeared to have no effect on the carbon or nitrogen contents of the soil.

[3] Since 1897.

rapidly to begin with, and then more slowly to a figure characteristic for the system of farming on the soil:[1] the losses of nitrogen consequent upon this change in land use are discussed on p. 301.

Adding farmyard manure regularly to an arable soil either increases its organic matter, if it had previously reached an equilibrium value, or else reduces its rate of loss, if that is occurring. Thus, on Broadbalk field, which has been in continuous wheat since 1843, the nitrogen content in the top 9 inches of soil on the unmanured plot and the plot receiving no nitrogen fertilisers has remained steady at about 0·10 per cent, whilst that on the plot receiving an annual dressing of 86 lb. of nitrogen as sulphate of ammonia has remained steady at about 0·12 per cent,[2] as shown in Table 62.

TABLE 62

Nitrogen Percentage in the top 9 in. of Broadbalk Soils

Plot	3	5	7	2A	2B
Manuring	None	PK	NPK	Farmyard manure	
				Since 1885	Since 1843
Year					
1865 . . .	0·105	0·106	0·117	—	0·175
1881 . . .	0·101	0·107	0·121	—	0·184
1893 . . .	0·094	0·101	0·115	0·136	0·213
1914 . . .	0·093	0·103	0·115	0·191	0·236[3]
1936 . . .	0·103	0·105	0·120	0·186	0·226
1945 . . .	0·105	0·106	0·123	0·194	0·236

On the other hand, annual dressings of 14 tons per acre of farmyard manure, which contains about 200 lb. of nitrogen, doubled the nitrogen content in fifty years, and brought it to a nearly stable value of 0·24 per cent in 70 years. However, on the neighbouring half plot, which only began to receive 14 tons of manure in 1885, the nitrogen content reached 0·19 per cent in 1914, and has now stabilised at this figure. The apparent discrepancy between the two half plots is probably due to the fallowing that has had to be introduced into this field for weed control since 1925.

[1] For an example of this from the Waite Institute, Adelaide, see G. B. Clarke and T. J. Marshall, *Aust. J. Counc. Sci. Indust. Res.*, 1947, **20**, 162.

[2] E. M. Crowther, *C.R. Conf. Pédol. Méditerr.*, 1947, 123. W. H. Metzger, *Kansas Agric. Expt. Sta., Tech. Bull.* 45, 1939, and J. Elson, *Soil Sci.*, 1943, **56**, 235, have also given illustrations of the ability of nitrogen fertilisers to maintain a higher nitrogen content in the soil, due to the larger growth of the crop they produce.

[3] Only one sample; the duplicate sample gave a nitrogen content of 0·266, probably through a bit of manure being included.

The 1945 samples were taken from a large number of holes per plot, the samples for the other years from a very few.

Since 1930 the land is fallowed one year in five, and this fallowing appears to have slowed up the rate of accumulation of organic matter on plot 2A very appreciably without effecting the level of nitrogen in plot 2B.

These results for the effect of farmyard manure on the nitrogen content of the soil enable one to make rough calculations of the proportion of the carbon and nitrogen in the manure that enters the humus supply in the soil. During the first fifty years of plot 2B the soil gained annually about 50 lb. of nitrogen and about 500 lb. of carbon, and received annually about 200 lb. of nitrogen and 3,800 lb. of carbon in the manure. Thus, over the first fifty years about one-quarter of the added nitrogen and one-eighth of the added carbon remained behind in the soil as slowly decomposable humus, and this fraction was probably 50 per cent higher in the first twenty years.

Crowther has further shown that on the light soil at Woburn, which was cropped to wheat or barley continuously for fifty years, the nitrogen content fell from 0·16 to 0·10 per cent during this period if no farmyard manure was given, but it was maintained at about this level when 6 to 7 tons per acre was given. Again, comparing the plots receiving farmyard manure with those receiving none, about 30 per cent of the nitrogen supplied by the farmyard manure remained in the soil, though in the five years immediately after this period when two fallows and three corn crops were taken without any manure being added, half of the additional nitrogen in the farmyard manure plots was lost. Again, in some Danish experiments at Lyngby,[1] where land was cropped to a six-course rotation and some plots given farmyard manure twice in the rotation, the soils retained 32 per cent of the nitrogen added in the manure during four courses of the rotation. Thus, under normal arable conditions in north-west Europe, soils receiving regular additions of farmyard manure retain between one-quarter and one-third of the nitrogen in the manure, in the form of soil organic matter having a C/N ratio of about 10.

[1] Described by K. Dorph-Petersen, *Tidskr. Planteavl*, 1946, **50**, 555.

CHAPTER XVI

THE NITROGEN CYCLE IN THE SOIL

The Mineralisation of Soil Nitrogen

Mineralisation of soil nitrogen is the name used for the process by which nitrogen in organic compounds becomes converted into the inorganic ammonium and nitrate ions. The transformation can probably only take place through the stages

organic N → ammonia → nitrite → nitrate

and as far as is known these transformations are predominantly brought about in the soil by micro-organisms.

THE PRODUCTION OF AMMONIA FROM ORGANIC MATTER

The soil microflora typically produce ammonia from organic compounds when they set free more nitrogen from the organic matter on which they are living than they can assimilate into their own protoplasm. Further, ammonia forms their sole important nitrogen excretion product under aerobic conditions, though if the oxygen supply is restricted amines may also be produced. Ammonia production from nitrogen-rich organic matter is thus not confined to a few groups of soil micro-organisms: it is their typical and characteristic nitrogen excretion product. Soil animals, on the other hand, probably excrete either uric acid, as in the insects, or urea as in the mammals.

This concept of ammonia production being the nitrogen waste-product in the conversion of organic matter into microbial tissue and vital energy—originally put forward by E. Marchal[1] in 1893—is fundamental for understanding the effect of adding different types of organic matter on the mineral nitrogen in the soil. Thus, when a protein, such as dried blood, is added to a soil, about 80 per cent of the added nitrogen is liberated as ammonia, the remainder of the nitrogen being retained in microbial tissue; but as increasing quantities of a carbohydrate, such as cellulose, is mixed in with the protein, so the amount of microbial tissue that can be built up is increased, with the consequence that the proportion of nitrogen liberated as ammonia decreases until the ratio of carbohydrate to protein reaches a ratio of about 5 : 1 when all the nitrogen in the dried blood is needed by the micro-organisms.

[1] *Bull. Acad. Roy. Belg.*, 1893 (3), **25**, 727.

There is some evidence that ammonia can be produced in soils treated with toluene, and therefore presumably not by the action of living micro-organisms. This seems to have been first noted by E. J. Russell and H. B. Hutchinson[1] in 1909, but it has recently been re-examined in more detail by J. P. Conrad,[2] who showed that soils so treated still possess the power to decompose urea and some other amides, presumably hydrolysing them to ammonium carbonate either by the enzyme urease, which is released into the soil from the decomposing plant and animal tissues there, or by a somewhat similar enzyme. Whether uric acid—the nitrogen excretion product of most soil invertebrates—is similarly decomposed has not been investigated.

NITRIFICATION IN THE SOIL: THE PRODUCTION OF NITRITE AND NITRATE

Th. Schloesing and A. Müntz[3] proved in 1877 that nitrification, used here to mean the production of nitrate from ammonia, was mainly a biological process by showing it could be stopped by antiseptics such as chloroform; and this is still the only process that is definitely known to bring about this oxidation in soils.

Various claims have been put forward that nitrate can be produced photochemically from organic compounds, but these have not yet been substantiated.[4] There seems little doubt that ammonia can be oxidised photochemically to nitrite in solution,[5] but it appears that nitrates are more liable to photochemical reduction to nitrites than the other way round. The importance of this photo-oxidation to nitrite even in tropical soils, where it can only be a surface phenomenon, is still undecided. Corbet has also claimed that nitrites can be oxidised catalytically by hydrogen ions to nitrates in the presence of free oxygen if the *p*H is below 5, but again there is no direct evidence that this process actually takes place in the field.

Our knowledge of the detailed processes by which micro-organisms produce nitrate in the soil is surprisingly scanty considering the importance of this oxidation. The following facts have probably been established:

1. Nitrate is always produced from nitrite.
2. Nitrate formation can only go on in the presence of a generous oxygen supply.
3. The oxidation of ammonia in the soil takes place on the surface

[1] *J. Agric. Sci.*, 1909, **3**, 111.
[2] *Soil Sci.*, 1942, **54**, 367; *J. Amer. Soc. Agron.*, 1941, **33**, 800; 1942, **34**, 1102; *Proc. Soil Sci. Soc. Amer.*, 1944, **8**, 171.
[3] *C.R.*, 1877, **84**, 301; **85**, 1018; 1878, **86**, 982.
[4] For a review, see S. A. Waksman and M. R. Madhok, *Soil Sci.*, 1937, **44**, 361.
[5] G. G. Rao and N. R. Dhar, *Soil Sci.*, 1931, **31**, 379; A. S. Corbet, *Biochem. J.*, 1934, **28**, 1575; B. N. Singh and K. M. Nair, *Soil Sci.*, 1939, **47**, 285.

of the soil particles, and it is only exchangeable ammonium ions that are oxidised. Hence, increasing the total amount of these exchangeable ions increases the maximum rate of ammonia oxidation.[1]

4. The oxidation only goes on rapidly if there is a good supply of calcium and phosphate, and if there is a proper balance of the trace elements iron, copper and zinc.[2]

5. The micro-organisms concerned in the oxidation are bacteria.

It had until recently always been assumed that nitrite could only be formed from ammonia, and this may well be the sole source of nitrite in the soil, but J. H. Quastel and P. G. Scholefield[3] claim to have shown that there are organisms present in the soil which will produce nitrite direct from pyruvic and oxalacetic oximes, and that the organisms carrying out these oxidations cannot oxidise ammonia. It is possible that pyruvic oxime is a very fugitive metabolic product in the soil, and if so, it could be the precursor of some of the nitrate formed from the decomposition of organic nitrogen compounds.

Strong direct evidence has recently been produced to show that nitrate formation in soils takes place through the nitrite stage. Thus, W. P. Martin[4] and his associates found that if ammonia or urea is added to Arizona desert soils with *p*H above 7·7, between a quarter and a third of the added nitrogen appears as nitrite before nitrate formation starts. Further, H. Lees and J. H. Quastel[5] found that, when circulating a solution of ammonium sulphate through a soil under aerobic conditions, they could delay the onset of nitrate production by adding some potassium chlorate to the solution, and this delay was solely due to stopping nitrite oxidation and not nitrite formation. They showed that this inhibiting effect of the chlorate was probably due to its power of very greatly reducing the speed with which the nitrite-oxidising organisms could proliferate, as the chlorate had no effect on the velocity of oxidation of nitrite to nitrate in the presence of an adequate number of nitrite-oxidising organisms. This inhibiting effect was itself inhibited in the presence of an adequate supply of nitrate. Only chlorate, of all the salts tried, had this effect, and only nitrate, of all the salts tried, could neutralise this specific effect of chlorates. This work, therefore, strongly suggests that, in the Rothamsted soils at least—and these were the only soils used in this work—the power of oxidising nitrites is confined to a very limited number of closely related organisms, although it need only prove that the organisms have the same nutritional needs for growth.

[1] H. Lees and J. H. Quastel, *Biochem. J.*, 1946, **40**, 815.
[2] H. Lees and J. Meiklejohn, *Nature*, 1948, **161**, 398; *Biochem. J.*, 1948, **42**, 534.
[3] *Nature*, 1949, **164**, 1068.
[4] W. P. Martin, T. F. Buehrer and A. B. Caster, *Proc. Soil Sci. Soc. Amer.*, 1943, **7**, 223; *Arizona Agric. Expt. Sta., Tech. Bull.* 96, 1942.
[5] *Biochem. J.*, 1946, **40**, 824.

There has been some discussion in the past on whether the oxidation of ammonia to nitrite goes through intermediate compounds such as hydroxylamine and hyponitrous acid. R. M. Beesley[1] showed that there is a considerable disappearance of ammonia in the initial stages of its oxidation before any appreciable amount of nitrite or nitrate can be detected—a result also found by W. P. Martin and his associates[2] when urea or ammonium salts were added to alkaline Arizona soils. Beesley suggested that this was due to an intermediate product being produced, and the suggestion arose that it was either hydroxylamine or hyponitrous acid. There are no accurate and simple specific tests for these two substances, though A. S. Corbet[3] claimed to have devised one for hyponitrous acid and to have demonstrated that both of these compounds were intermediates in the production of nitrite. Subsequent work, however, has failed to confirm the presence of hydroxylamine and has shown that Corbet's test for hyponitrites is not specific[4]. Further, H. Lees[5] has shown that soils in which ammonia can be rapidly oxidised to nitrate through nitrite are incapable of oxidising hydroxylamine to nitrite when present in solutions sufficiently dilute not to injure the bacterial population. And hyponitrites are so unstable in soils that it is extremely unlikely they could ever be present in quantities approaching that needed to account for the disappearance of ammonium before the production of nitrite ions. Thus if the correct explanation of Beesley's and Martin's phenomenon is that an intermediary compound is formed, it must be an organic one.

The only agents that have so far been proved to oxidise ammonia to nitrites and nitrites to nitrates in soil are bacteria, but the technique for isolating the organisms responsible for the oxidation of ammonia to nitrite and nitrite to nitrate is troublesome. Long ago R. Warington, at Rothamsted,[6] obtained bacterial cultures, which must have been very mixed, that would convert ammonia and some organic nitrogen compounds into nitrites, but not necessarily nitrates, and others that would convert nitrites, but not ammonia, into nitrates; but he could not isolate these organisms as pure cultures on gelatin. It was left to S. Winogradsky,[7] to isolate the bacteria responsible. He argued that the organisms should be autotrophic, obtaining their carbon from CO_2 and their energy from the oxidation of ammonia and nitrite, and that therefore they alone of the soil organisms should grow on silica gel

[1] *Trans. Chem. Soc.*, 1914, **105**, 1014. [2] *Proc. Soil Sci. Soc. Amer.*, 1942, **7**, 223.
[3] *Biochem. J.*, 1934, **28**, 1575; 1935, **29**, 1086.
[4] W. V. S. Rao, P. V. Krishnamurti and G. G. Rao, *J. Indian Chem. Soc.*, 1938, **15**, 599.
[5] *Nature*, 1948, **162**, 702.
[6] It is instructive to read his papers on this subject (*Trans. Chem. Soc.*, 1878, **33**, 44; 1879, **35**, 429; 1884, **45**, 637; 1888, **53**, 727; 1891, **59**, 484) and to realise that in spite of the far better techniques available to-day many of the problems raised are still unsolved.
[7] *Ann. Inst. Pasteur*, 1890, **4**, 213, 257, 760; with W. Omeliansky, *Zbl. Bakt.* II, 1899, **5**, 329, 429; *Arch. Sci. Biol.* (*St. Petersburg*), 1899, **7**, No. 3.

plates free from organic matter but containing ammonium salts or nitrites. Using this technique, he isolated an ammonium oxidising and nitrite producing bacterium, which he called *Nitrosomonas*, and a nitrite oxidising and nitrate producing bacterium, which he named *Nitrobacter*. He found these bacteria needed free calcium or magnesium carbonate on which to grow and were harmed, in solution cultures, by some organic compounds such as glucose and peptone, though they were stimulated by others such as acetates[1] and a decoction of horse dung. He also found that they were slow growing and only formed very small colonies, and hence would be very difficult to isolate by any other technique.

These two bacteria have been found by several other workers who have looked for them, but the technique requires considerable skill and the colonies are very small, about 0·1 mm. in diameter.[2] Most of the characteristics claimed for them by Winogradsky have been confirmed by other workers, though T. Y. Kingma Boltjes[3] could not confirm that glucose was toxic, but found that the toxicity of peptone depended on its free amino acid content, suggesting that some amino acid is toxic to them. J. H. Quastel[4] has carried these results further by showing that methionine is a very powerful inhibitor of nitrification, inhibiting both the oxidation of ammonia and nitrite.

It is still uncertain if *Nitrosomonas* and *Nitrobacter* are the sole ammonium and nitrate oxidising organisms in the soil. Winogradsky described a second ammonium oxidiser, *Nitrosococcus*, at the same time as he described *Nitrosomonas*, and he and his daughter, H. Winogradsky,[5] described several others, but doubt has been cast on the ability of these to nitrify.[6] Further, D. W. Cutler and B. K. Mukherjee[7] claimed to have isolated heterotrophic organisms which could produce traces of nitrite from ammonia, but it is possible that the nitrite they detected was produced by the reduction of small quantities of nitrates which may have been present in their solutions as impurities.

Nitrification only takes place readily in moist, well-aerated soils. It is inhibited by low and high temperatures, taking place very slowly below 4° C. or above 40° C., and reaching its maximum rate around 30° C.[8] Hence, the proportion of ammonium to nitrate ions increases at low and very high temperatures. Nitrification also requires adequate supplies of available phosphate and calcium, and a proper balance of

[1] For some recent work on this, see H. Bomecke, *Arch. Mikrobiol.*, 1939, **10**, 385.

[2] For a recent discussion of the technique with a review of the literature, see J. Meiklejohn, *Nature*, 1949, **164**, 667; *J. Gen. Microbiol.*, 1950, **4**, 185.

[3] *Arch. Mikrobiol.*, 1935, **6**, 79.

[4] *Nature*, 1949, **164**, 1068.

[5] *Ann. Inst. Pasteur*, 1933, **50**, 350.

[6] A. A. Imsenecki, *C.R. Acad. Sci.* (*U.S.S.R.*), 1945, **47**, 229; *Nature*, 1946, **157**, 877.

[7] *Proc. Roy. Soc.*, 1931, **108** B, 384.

[8] For examples, see H. L. Jensen, *Proc. Linn. Soc., N.S.W.*, 1939, **64**, 601; F. C. Gerretsen, *Landbouwk. Tijdschr.*, 1942, **54**, 573.

the minor elements iron, manganese and copper, but the conditions have not been worked out in detail. Thus, Bornebusch[1] found that the rate of nitrification exceeded the rate of ammonification in acid forest soils in the *p*H range 4–5·5 when mull formation was taking place, but not when raw humus is being formed, as shown in Table 63.

TABLE 63

The Effect of Type of Humus on Nitrification

Parts per million of ammonium and nitrate nitrogen in the soil

Mull Soils				Raw Humus Soils			
Under Beech							
Layer:	*p*H	NH_4	NO_3	Layer:	*p*H	NH_4	NO_3
Old leaf litter	6·1	84	1200	Old leaf layer	5·6	252	20
Wormcasts	5·8	8	264	Upper raw humus	4·3	388	trace
Upper mull	5·4	4	48	Middle raw humus	3·7	95	trace
Lower mull	5·2	2	7·5				
Under Spruce							
Mull layer	4·3	80	26	Upper raw humus	3·6	115	0·8
Upper top soil	4·1	2	5	Middle raw humus	3·5	32	trace

This is possibly due to mull soils being richer in bases and in phosphates than raw humus soils, for H. L. Richardson[2] has shown that a lack of calcium and of phosphate[3] limits the rate of nitrification on some of the starved permanent grass plots at Rothamsted.

Typically, the process of nitrite oxidation goes on faster than nitrite production, so that the nitrite level in soils is usually much lower than that of ammonia or nitrates. But conditions can arise, in some desert soils, for example, when nitrite production exceeds nitrite oxidation, with the consequence that nitrites may temporarily accumulate in the soil solution sufficiently to lower the vitality of the crop growing on that soil, so rendering it susceptible to a number of diseases. The cause of this inversion of the oxidation rates is not known, but it is possibly due to the nitrite producers having a lower phosphate requirement at high *p*Hs than the nitrite oxidisers;[4] and if this is so, it might explain an observation of G. Drouineau and his co-workers[5] that nitrite accumulation can take place in soils to which very large amounts

[1] *Forstl. Forsoegsv. Daumark*, 1930, **11**, 1. [2] *J. Agric. Sci.*, 1938, **28**, 73.

[3] See G. S. Fraps and A. J. Sterges (*Soil Sci.*, 1939, **47**, 115) for further examples of this effect.

[4] See, for example, G. S. Fraps and A. J. Sterges, *Soil Sci.*, 1939, **47**, 115; A. B. Caster, W. P. Martin and T. F. Buehrer, *Arizona Agric. Expt. Sta., Tech. Bull.* 96, 1942.

[5] *C.R.*, 1948, **226**, 957.

of calcium carbonate have been added. It is also possible that part of the harmful effect of chlorates on plant growth may be that they stop the oxidation of ammonia at the nitrite stage, so that it is the nitrite rather than the chlorate that is directly poisoning the plant.

THE LEVEL OF MINERAL NITROGEN IN THE SOIL

The mineral nitrogen in the soil is present either as ammonium or nitrate ions. The nitrates are all dissolved in the soil solution, unless the soil dries out, but much of the ammonium is held on the exchange complex. The total quantity of mineral nitrogen in the soil is the difference between the rate it is being produced from the soil's store of organic matter by the soil population and the rate it is being removed by leaching, by growing crops and by other members of the soil population; and the proportion of nitrate to ammonia depends also on the rate of oxidation of ammonia to nitrates, the uptake of nitrates by the plant and the loss of nitrates by leaching.

Grassland soils have the main proportion of their mineral nitrogen present as ammonia, as is shown in Table 64, for the Rothamsted soil.[1]

TABLE 64

Average Ammonium and Nitrate Contents of Rothamsted Grassland Soils

Years under grass	Depth of sampling in cm.	Nitrogen in parts per million of dry soil	
		Present as ammonium	Present as nitrate
Ley under 1	20	1·1	0·5
Ley under 2	20	2·2	1·1
Pasture, 59	10	4·7	1·3
Pasture, over 200	20	5·4	1·1

Further, both the ammonium and nitrate levels remain very constant throughout the year, and even large additions of ammonium or nitrate fertilisers only affect them for short periods.

Arable soils, particularly if they are not too acid, have a fairly constant but low content of ammonium nitrogen, but a very variable nitrate content ranging from 2 to 20 mgm. of nitrogen as nitrate per kg. of soil (i.e. 2 to 20 parts per million of nitrate nitrogen) for normal soils, but rising up to 60 mgm. for rich garden soils and,

[1] H. L. Richardson, *J. Agric. Sci.*, 1938, **28**, 73.

according to G. ap Griffith,[1] rising to 100 mgm. for some tropical soils during the dry season. This nitrate content varies throughout the season and, under some conditions which cannot yet be specified, from hour to hour.[2] Fig. 22 shows the nitrate nitrogen content, throughout the growing season of 1915, of two parts of the Broadbalk plot at Rothamsted which receives farmyard manure annually, one part being cropped to wheat and one part fallowed.[3] Not all the details of these curves can be explained, but the figure shows clearly that the fallow

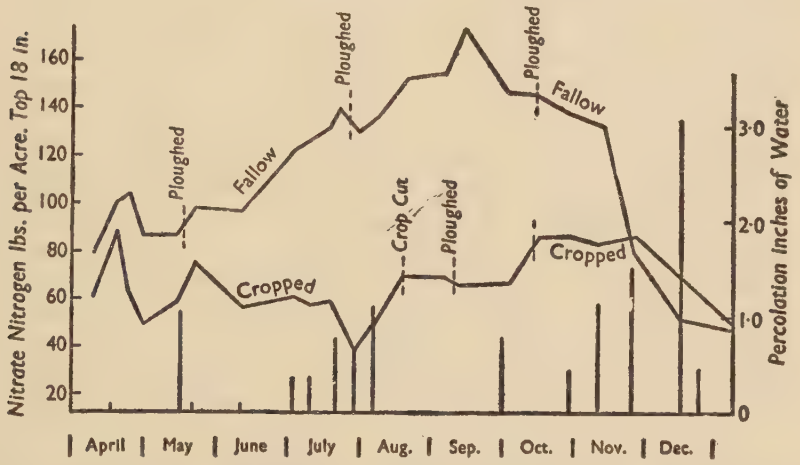


FIG. 22. Amount of nitrate nitrogen in cropped and fallow soils at different seasons of the year and the amount of percolation through the 20-in. bare soil gauge (Broadbalk Field, Rothamsted, 1915).

soil accumulates nitrates during the spring and summer, whereas the cropped soil does not, and that the fallow appears to have lost all its accumulated nitrates by early winter, presumably due to them being leached down into the deep subsoil. Fallows can, however, only accumulate nitrates under four conditions: they must be kept free from weeds; there must be decomposable organic matter in the soil; the soil must be moist, otherwise the micro-organisms cannot work; and there must not be too much rain, otherwise the nitrates will get washed out of the soil as soon as they are formed. Some results of W. E. de B. Diamond,[4] working with tropical arable soils at Ibadan, Nigeria, illustrate these points; nitrates can only accumulate in these soils during the beginning

[1] *Commonw. Bur. Soil Sci., Tech. Comm.* 46, 1949.

[2] H. G. Thornton and P. H. H. Gray, *Proc. Roy. Soc.*, 1930, **166** B, 399.

[3] E. J. Russell and A. Appleyard, *J. Agric. Sci.*, 1917, **8**, 385. For a further example, see W. A. Albrecht, *Missouri Agric. Expt. Sta., Res. Bull.* 250, 1937.

[4] *Emp. J. Expt. Agric.*, 1937, **5**, 264. For some S. African results, see T. D. Hall, *Soil Sci.*, 1921, **12**, 301; for some Australian, J. A. Prescott and G. R. Piper, *J. Agric. Sci.*, 1930, **20**, 517; and for some West Indian, F. Hardy, *Trop. Agric. Trin.*, 1946, **23**, 40.

and the end of the rainy season, for they are washed out, or taken up by the crop during the main part of the rains, and the soil soon becomes too dry for them to be produced during the dry season.

F. Crowther,[1] working in the Sudan Gezirah, has also given a good example of weeds reducing the accumulation of nitrates in a fallow soil. This heavy clay land is commonly fallowed for several years in preparation for cotton, and Crowther showed that cutting down the weeds that grew during the short rainy season, instead of letting them die as soon as the dry season began, increased the nitrate nitrogen in the top foot of soil from 2–4 p.p.m. to 5–10 p.p.m., and also increased that in the second foot. This led to a 66 per cent increase in the uptake of nitrogen by the cotton and a corresponding increase in the yield of seed-cotton.

There have been many claims made that the growing crop interferes with the production of nitrate in a soil. The type of evidence used to show this is illustrated by Table 65, which gives the nitrate nitrogen in the soil of neighbouring plots of cropped and fallow land at Rothamsted.[2] But the interpretation of this table is not simple, as no allowance was made for the nitrogen in the living or dead root system of the crop—a quantity that is extremely difficult to estimate. This deficiency is, however, built up before the crop comes to maturity, for in 1915 the rate of nitrate production is seen to be as high under wheat as under fallow between July 26th and August 17th—the day after the wheat was cut. A part of this deficit could also be due to reduced nitrate production under the crop due to the extra drying-out of the soil by the crop compared with the fallow, though if this was important one would have expected the deficit to be smaller in 1912, a year with a wet, late spring and summer and with the plot carrying a small crop, than in 1911, when the late spring and summer was drier, the temperature higher and the crop larger. Hence, the crop may have some specific effect in reducing the rate of nitrate production for reasons other than those already discussed; or there may be an additional process operative in the presence of a growing crop that can lock up nitrates. The microbial population around the plant roots could produce just this effect if they could extract from the root system, or if the roots excrete, an appreciable amount of carbohydrates.

Nitrate production is naturally a process requiring a good oxygen supply, hence can only take place rapidly in well-drained soils. Various workers have claimed that even in such soils it can be increased if the soil is kept deeply cultivated, a process which presumably improves the aeration of the subsoil. The experimental evidence on this point

[1] *Emp. J. Expt. Agric.*, 1943, **11**, 1.
[2] E. J. Russell, *J. Agric. Sci.*, 1914, **6**, 18; with A. Appleyard, ibid., 1917, **8**, 385.

TABLE 65

Nitrogen as Nitrate in Cropped and Fallow Soil at Rothamsted

Crop—Wheat

As pounds of nitrogen per acre

	Hoosfield		Broadbalk		
	June 1911	July 1912	Unmanured	Dunged	
			July 1915	26th July 1915	17th Aug. 1915
In top 18 in. of fallow soil .	54	46	70	124	150
In top 18 in. of cropped soil	15	13	44	37	69
In crop	23	6	21	70	70
Total	38	19	65	107	139
Deficit in cropped land .	16	27	5	17	11
Expressed as mgm. N per kg. soil					
Fallow, 0–9 in. depth . .	12	8			
9–18 in. depth .	9	10			
Cropped, 0–9 in. depth .	4	2			
9–18 in. depth .	2	3			

Cropping. Hoosfield: Alternate wheat and fallow, unmanured since 1851.
Broadbalk: Continuous wheat, but fallow taken over part of this field for the third time since 1843.

is, however, very scanty, and in some of those which appear to show a beneficial effect of cultivation, the possibility that it was due to a better control of the weeds rather than better aeration cannot be ruled out.

Losses of Inorganic Nitrogen from the Soil

The inorganic nitrogen compounds—ammonia and nitrates—suffer several types of loss from the soil. They may be taken up by growing plants, they may be assimilated into the bodies of micro-organisms and so brought back into the organic nitrogen reservoir, they may be converted into volatile compounds and lost into the air, or they may be leached out of the soil. It is only the last two losses that will be considered here.

Many bacteria, and possibly some actinomycetes when growing in conditions of a limited oxygen supply, can use nitrates and other

inorganic ions such as sulphates and ferric ions instead of, or in partial replacement of, atmospheric oxygen as the hydrogen acceptor needed in their respiration processes. Some common soil bacteria[1] will still do this even under well-aerated conditions. Nitrates are thus reduced to nitrites, oxides of nitrogen, nitrogen gas, and ammonia, the relative proportions produced depending on the type of bacteria and the conditions in which they are working. The whole process is sometimes known as denitrification and it contains the only biological process known which returns nitrogen gas to the atmosphere. There is a possibility that nitrogen gas may also be liberated by a chemical process under acid conditions,[2] for nitrites can react with amines to give nitrogen gas, thus

$$R.NH_2 + HNO_2 \rightarrow R.OH + N_2 + H_2O$$

but there is no evidence this reaction is of any importance in the soil.

The conditions conducive to gaseous nitrogen loss in soils have not been worked out in detail, but, unless nitrates are being added to the soil, they must include periods of nitrate formation followed by periods of nitrate reduction, that is, alternating periods of good and bad aeration.[3] M. P. Korsakova[4] found some bacteria, under suitable conditions, can decompose nitrates almost quantitatively to nitrogen gas via nitrites and some unidentified intermediate compound, as shown in Fig 23. In general, a good supply of decomposable organic matter, a high nitrate supply and impeded drainage are the optimum conditions for nitrogen loss by this means.

Nitrogen can, however, be lost to the atmosphere in the form of ammonia, and this may be of considerable importance in alkaline soils under hot, wet conditions such as occur in many flooded paddy rice fields.[5] The primary condition necessary for this loss is that ammonia production should go on faster than ammonia oxidation; for as soon as ammonia begins to accumulate near the soil surface in neutral soils it is liable to loss by volatilisation. Water-logging can obviously lead to this condition—for rapid nitrification needs a good air supply—but so also can high temperatures. Thus, C. M. Hutchinson[6] found with some Indian soils that nitrification can keep pace with ammonification if the temperature is about 20° C.; but at 30° C. ammonification goes so rapidly that it appears to inhibit nitrification, possibly because it

[1] J. Meiklejohn, *Ann. Appl. Biol.*, 1940, **27**, 558.
[2] N. W. Barritt, *Biochem. J.*, 1931, **25**, 1965.
[3] E. J. Russell and E. H. Richards (*J. Agric. Sci.*, 1917, **8**, 495), showed the necessity of this for gaseous nitrogen losses from manure heaps.
[4] Quoted by E. E. Uspensky, *Soil Microbiology in the U.S.S.R.*, Moscow, 1933.
[5] See, for example, W. H. Willis and M. B. Sturgis, *Proc. Soil Sci. Soc. Amer.*, 1945, **9**, 106.
[6] *Mem. Dept. Agric. India, Bact. Ser.*, 1912, **1**, 1.

causes a too rapid rise of *p*H with a consequent depression of available phosphates (p. 451).

The method of conserving nitrogen under these two conditions is, however, entirely different. In typical alkaline paddy fields the ammonia can only be kept low by adding complex organic nitrogen compounds that are only slowly ammonified; but under hot, alkaline, arid conditions the loss can also be kept low by using nitrate rather than ammonium fertilisers. Thus, F. Crowther[1] found sulphate of

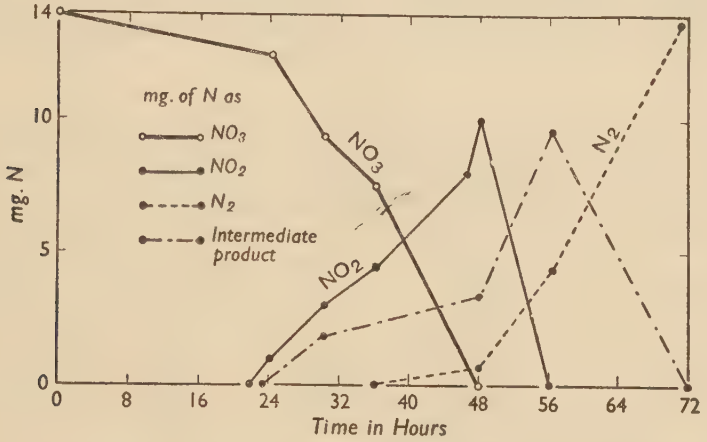


FIG. 23. Bacterial reduction of nitrate. The hypothetical intermediate product accounts for the difference between the numbers of mgm. of products obtained and 14 mgm.

ammonia was a less efficient source of nitrogen for irrigated cotton on the heavy alkaline Gezirah soil than calcium nitrate, and in fact about 20 lb. of the nitrogen added as sulphate of ammonia seemed to be lost when it was applied as a top dressing, though from the indirect evidence given in his paper it would appear to have been about as efficient as the nitrate, if it had been drilled 6 inches deep instead of being broadcast. T. N. Jewitt[2] confirmed that in fact there is a considerable loss of ammonia from this soil when ammonium sulphate is applied to its surface.

Nitrogen losses, as ammonia, from soils may also occur under English conditions when readily decomposable nitrogen-rich organic matter is mixed with the superficial layer of the soil. Thus, J. A. Daji,[3] working at Woburn, found that up to 40 per cent of the nitrogen of young mustard or tare plants was lost from the soil in two months, compared with no loss of the nitrogen of mature mustard plants over the same period.

[1] *Emp. J. Expt. Agric.*, 1941, **9**, 125. [2] *Soil Sci.*, 1942, **54**, 401
[3] *J. Agric. Sci.*, 1934, **24** 15.

Nitrogen can also be lost from the soil by the nitrates in the soil solution being leached out either into the subsoil or into the drainage water, and this loss can be sufficient to account for the total loss of nitrogen from bare fallow soils under English conditions. As an example, the soil in the Rothamsted drain gauges, the surface of which has been kept free from vegetation since 1870, had lost one-third of the nitrogen originally present in the top 9 inches by 1915, but as shown in Table 66, the amount of nitrogen found as nitrates in the drainage water was approximately equal to the loss of nitrogen from the soil, thus proving that this loss of soil nitrogen is mainly due to the leaching out of nitrates under these conditions.

TABLE 66

The Nitrogen Balance Sheet of a Soil kept Free from Vegetation but Exposed to Rain and Weather[1]

Year	Per cent N in soil, top 9 in.	N in soil, top 9 in. lb. per acre	Loss of N from top 9 in. lb. per acre	N recovered as nitrate 1870–1915 lb. per acre[2]
1870 . . .	0·146	3500	—	—
1905 . . .	0·102	2450	1050	987
1915 . . .	0·098	2350	1150	1223

In field conditions where plants are growing in the soil the amount of drainage water is less than on the uncropped gauge, and the loss of nitrate is further reduced by any factor that improves plant growth. On the Broadbalk wheat field, the autumn drainage water from plots receiving sulphate of ammonia alone, and yielding about 11 cwt. of grain, contains on an average 18 parts per million of nitric nitrogen, whilst that on the plot receiving in addition potassic and phosphatic fertiliser, and yielding about 16 cwt. of grain, contains only 8·5 parts per million.

In the uncropped drain gauge there is no addition of vegetable matter to the soil, and consequently there is nothing in the nature of easily decomposable organic matter present. Growing plants, and particularly farmyard manure, add this kind of material, and therefore open up the possibility of losses of nitrogen to the atmosphere, as described above.

[1] Constructed from data given by N. H. J. Miller, *J. Agric. Sci.*, 1906, **1**, 377, and E. J. Russell and E. H. Richards, ibid., 1920, **10**, 22.

[2] After deducting the amount brought down in the rain. No significance should be attached to the difference between the last two columns owing to the assumptions involved in obtaining, and the uncertainties in interpreting, the figure for the weight of nitrogen in the top 9 inches of the soil.

Some drainage results at Cornell indicate that crops themselves can cause considerable losses of nitrogen from soils if they are very well supplied with available nitrogen. J. A. Bizzell[1] found that timothy and market-garden crops can cause up to one-third of the nitrogen added as sulphate of ammonia or nitrate of soda to be lost under these conditions. The reason for this loss is still uncertain, though J. K. Wilson[2] supposes it is due to the plants excreting drops of liquid containing nitrites and ammonia or other amines which react to give gaseous nitrogen. Table 67 gives an example of their losses, showing how they only occur with luxury consumptions of nitrogen by the crop.[3]

TABLE 67

Loss of Nitrogen from Soil under Crops Liberally Supplied with Inorganic Nitrogen (Cornell, N.Y.)

	Nitrogen changes in pounds of nitrogen per acre			
	Timothy (9-year period)		Market garden crops (15-year period)	
			Nitrogen as	
	High nitrogen	Low nitrogen	Sulphate of ammonia	Nitrate of soda
Lost from soil	—90	—40	470	710
Added as fertiliser and rain	1860	700	2230	2230
Total	1770	660	2700	2940
Removed in crop	1290	640	1400	1640
Removed in drainage water	40	20	630	690
Total	1330	660	2030	2330
Unaccounted for	440	—	670	610
As per cent added as fertiliser	24	—	31	28

These losses can also be illustrated on the Broadbalk wheat plot at Rothamsted, which receives annually 14 tons of farmyard manure per acre, supplying 200 lb. nitrogen. After allowing for the nitrogen taken

[1] *Cornell Agric. Expt. Sta., Mem.* 252, 1943; *Mem.* 256, 1944. For confirmatory evidence from California, see H. D. Chapman *et al.*, *Hilgardia*, 1949, **19**, 57

[2] *Cornell Agric. Expt. Sta., Mem.* 253, 1943.

[3] For an earlier example of this effect, see W. H. Pearsall and M. C. Billimoria, *Biochem., J.*, 1937, **31**, 1743.

up by the crop and left in the soil the deficit is enormous, being nearly 70 per cent of the nitrogen added. On the adjoining unmanured plot there is no deficit, the whole of the nitrogen lost from the soil being accounted for in the crop (Table 68).

TABLE 68

Losses of Nitrogen from a Cultivated Soil
Broadbalk, Rothamsted, 49 years, 1865–1914

Pounds per acre in top 9 inches of soil

	Farmyard manure (Plot 2B)	No manure (Plot 3)	Complete Artificials (86 lb. N as sulphate of ammonia annually)	
			(Plot 7)	(Plot 13)[1]
N in soil in 1865, lb. per acre	4850	2960	3390	3320
per cent	0·196	0·114	0·123	0·121
N in soil in 1914, lb. per acre	5590	2570	3210	3240
per cent	0·236	0·092	0·120	0·122
Total change in 49 years, lb. per acre	+740	−390	−180	− 80
N added in manure, seed and rain, per annum	208	7	93	93
N removed in crops, per annum	50	17	46	44
N retained (+) or lost (−) by soil per annum	+15	− 8	− 4	− 2
N unaccounted for, per annum	143	(gain 2)	51	51

Similar losses occur on the Woburn plots receiving farmyard manure annually,[2] and F. Scheffer[3] has given similar results for rye growing for fifty years at Halle under different fertiliser treatments. Unfortunately, it is not possible to form any estimate of the amount of nitrate washed out by rain-water, and so it is impossible to say what proportion of the nitrogen loss can be accounted for by leaching, and what must be assumed to be due to the volatilisation of ammonia or evolution of nitrogen gas.

Similar losses occur when grassland is converted into arable, or when virgin prairie soil is broken up for cropping. Oxidation and nitrification both proceed rapidly: part of the nitrate is taken up by the crop, but by far the greater part disappears and cannot be traced.

[1] These plots are almost duplicates, plot 7 receiving 100 lb. each of the sulphates of soda and magnesia in addition to the 3½ cwt. of superphosphate and 200 lb. sulphate of potash given to plot 13.

[2] *Fifty Years of Field Experiments at the Woburn Experimental Station*, E. J. Russell and J. A. Voelcker, with a Statistical Report by W. G. Cochran, London, 1936.

[3] *Arch. Landw. Abt. A*, 1931, **7**, 202.

It may be leached out, but the local observers usually consider this improbable. F. T. Shutt's[1] analyses of the Indian Head soil, Saskatchewan, are given in Table 69. Here there is but little drainage water, yet only one-third of the lost nitrogen is recovered in the crop. H. Snyder has given similar results for Minnesota[2] soils, C. O. Swanson[3] and P. L. Gainey[4] for Kansas soils, and A. F. Bracken and J. E. Greaves for Utah soils.[5]

TABLE 69

Losses of Nitrogen consequent on Breaking up of Prairie Land
Top 9 inches

	Per cent	Lb. per acre
Nitrogen present in unbroken prairie . . .	0·371	6940
Nitrogen present after 22 years' cultivation . .	0·254	4750
Loss from soil		2190
Recovered in crop		700
Deficit, being dead loss		1490
Annual dead loss		68

This unaccounted loss, occurring when prairie is broken up for arable, mainly occurs in the first few years of cultivation.[6] Thus, E. S. Hopkins and A. Leahey,[7] continuing Shutt's work at Indian Head, found that in the next sixteen years almost the whole of the loss of soil nitrogen could be accounted for by the nitrogen in the wheat. This loss only seems to occur, however, if the nitrogen content of the soil is high, for Myers[8] and his co-workers at Kansas showed that this loss of nitrogen was proportional to the nitrogen content of the soil in excess of its equilibrium value for the rotation adopted; thus for the wheat and barley rotations used, nitrogen losses only occurred if the nitrogen content of the soil exceeded 0·10 per cent.

Gains of Nitrogen by the Soil

Soils are always losing small amounts of nitrogen by one or more of the processes so far described; they must possess, therefore, some

[1] *J. Agric. Sci.*, 1910, **3**, 335.
[2] *Minnesota Agric. Expt. Sta., Bull.* No. 53, 1897.
[3] *Kansas Agric. Expt. Sta., Bull.* 199, 1914: *Bull.* 220, 1918.
[4] *Soil Sci.*, 1941, **51**, 1.
[5] *J. Amer. Soc. Agron.*, 1929, **21**, 1130.
[6] J. S. Burd and J. C. Martin, *Hilgardia*, 1931, **5**, 455.
[7] *Dom. Canada Dept. Agric., Publ.* 761, 1944.
[8] *Kansas Agric. Expt. Sta., Tech. Bull.* 56, 1943. For an example from the Canadian prairies, see J. D. Newton *et al.*, *Sci. Agric.*, 1945, **21**, 718.

methods for gaining it to balance these losses. Arable soils in the temperate regions, if allowed to revert either to natural forest or to pasture, rapidly gain nitrogen and organic matter. On Broadbalk field, for example, a third plot adjacent to the two quoted in Table 68 carried a wheat crop in 1882 which was never harvested: the plot was allowed to revert to natural prairie by cutting out all bushes and trees at regular intervals. A. D. Hall[1] found that in 1904, after twenty-two years, the vegetation consisted of 60 per cent grasses, 15 per cent miscellaneous herbs and 25 per cent legumes, mainly meadow vetchling (*Lathyrus pratensis*). The gains in nitrogen and organic matter during this period were considerable, as shown in Table 70. The nitrogen is all in organic compounds, for the nitrate and ammonia remain at low levels—the nitrate well below that of arable land and the ammonia a little above it. The gain in nitrogen in a neighbouring field, Geescroft, which carried clover in 1885 and was then allowed to go derelict, is also given in Table 70. This soil contains much less calcium carbonate, has about the same mechanical analysis, but it is much worse drained and lies water-logged for long periods. It also had a very unkind tilth for a number of years previously. In 1904 the grass *Aira caespitosa* composed 86 per cent of the plants present and legumes were almost entirely absent, composing only 0·4 per cent of the plants present; yet its annual gain of nitrogen was only about 35 per cent less than that of the Broadbalk plot.

TABLE 70

Gain in Nitrogen in Soils Permanently Covered with Vegetation Rothamsted Soils Left to Run Wild for over Twenty Years

	Broadbalk: $CaCO_3$, 3·32 per cent				Geescroft: $CaCO_3$, 0·16 per cent			
	Carbon, per cent		Nitrogen, per cent		Carbon, per cent		Nitrogen, per cent	
	1881	1904	1881	1904	1883	1904	1883	1904
1st 9 inches .	1·14	1·23	0·108	0·145	1·11	1·49	0·108	0·131
2nd 9 inches .	0·62	0·70	0·070	0·095	0·60	0·63	0·074	0·083
3rd 9 inches .	0·46	0·55	0·058	0·084	0·45	0·44	0·060	0·065
Approximate gain in nitrogen, lb. per acre				2200				1400
Lb. per acre per annum . . .				92				60

In the same way land laid down to pasture increases in nitrogen content: the typical nitrogen content of Rothamsted arable soils is about 0·11 per cent and of old grassland about 0·25 per cent, and

[1] *J. Agric. Sci.*, 1905, **1**, 241.

H. L. Richardson[1] estimated it takes about twenty-five years for half this gain to take place, as is shown in Fig. 24.

The most important process increasing the nitrogen content of agricultural soils is that brought about by bacteria living symbiotically in the nodules of leguminous plants, as discussed on p. 323: a good clover or lucerne crop will add annually over 100 lb. of nitrogen per acre to a soil, a quantity which can be measured without much difficulty. Symbiotic nitrogen fixation is probably not confined to leguminous plants, although they are agriculturally the only important

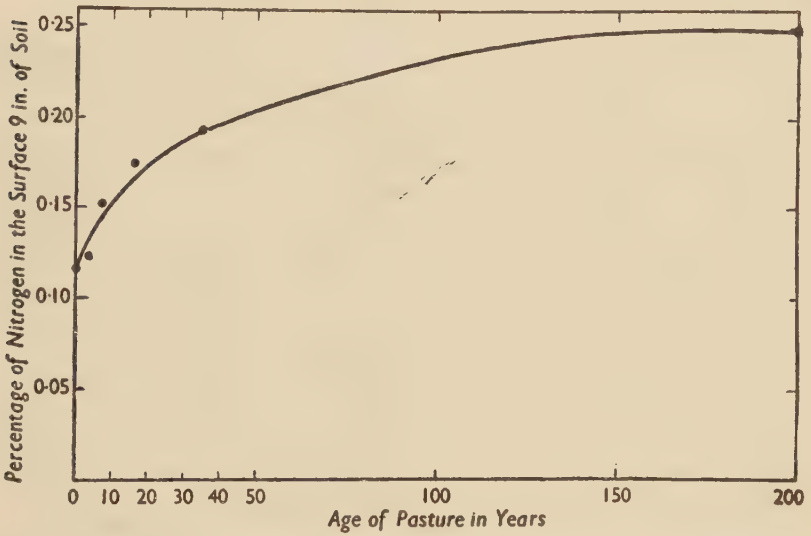


FIG. 24. The rate of accumulation of nitrogen in the top 9 in. of soil at Rothamsted when old arable land is laid down to grass.

nitrogen-fixing crops; it is probably also brought about by bacteria living in the root nodules of some trees of the subtropical genus *Casuarina*,[2] and in leaf-knots on some tropical shrubs of the family Rubiaceae, for example, *Pavetta*,[3] and *Chomelia*[4]—Pavetta leaves are in fact used as a nitrogenous green manure in Ceylon—and on the tropical monocotyledon *Dioscora*.[5] These leaf-knot bacteria appear to differ from the root nodule bacteria by being able to fix nitrogen when grown on simple media in pure culture. Thus, Rao found the leaf-knot bacteria on the Rubiaceae growing in mannitol could fix 10 to 15 mgm. of nitrogen per gm. of sugar decomposed. Nitrogen fixation is also

[1] *J. Agric. Sci.*, 1938, **28**, 73. [2] R. N. Aldrich-Blake, *Oxford Forestry Mem.*, No. 14, 1932.
[3] F. C. Faber, *Jahrb. wiss. Bot.*, 1912, **51**, 285.
[4] K. A. Rao, *Agric. J. India*, 1923, **18**, 132.
[5] M. Y. Orr, *Edinburgh Roy. Bot. Gardens, Notes*, 1924, **14**, 57.

brought about by an actinomycete living in root nodules on alder,[1] and possibly by fungi living in some ericaceous plants,[2] and in rye-grass.[3] All these statements are, however, in urgent need of verification using modern experimental techniques.

The soil may gain nitrogen by three other possible means. Rain-water contains ammoniacal and nitrate nitrogen. N. H. J. Miller[4] found that at Rothamsted the rain carried down about 4 lb. per acre of combined nitrogen annually, and workers in other parts of the world had previously obtained quantities varying from 2 to 20 lb. per acre.

Soils may be able to fix some nitrogen on their surface by photo-chemical action. N. R. Dhar and his co-workers in India have repeatedly claimed that nitrogen fixation occurs more rapidly in soils to which molasses, or other decomposable carbohydrates, have been added when they are exposed to the sunlight than when kept in the dark,[5] that a light dressing of cow manure added at the same time increases the efficiency of the carbohydrates, and that at least half the gain in nitrogen that takes place in the field when such materials are added to tropical soils must be due to photochemical action. This mechanism has not generally been accepted as important, but it is possible Dhar was dealing with conditions that allowed nitrogen-fixing blue-green algae to develop on the surface of his soils, and that they were responsible for the photochemical nitrogen fixation which he found.

Soils also contain free-living nitrogen-fixing organisms. So far only three groups have been generally recognised to have this power:

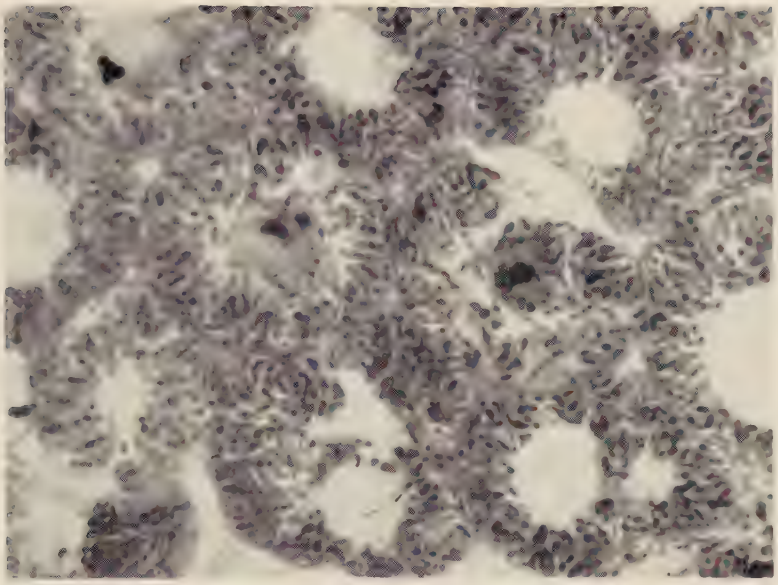
(1) facultative anaerobic bacteria of the *Clostridia* group;[6] their nitrogen fixing power in pure culture varies with the species used and with their nutritional history[7]—though this may be because their nutritional requirements for nitrogen fixation were not then known. They are probably of importance in forest soils,[8] and may be of importance in other soils in symbiosis with aerobes; (2) aerobic bacteria of the genus *Azotobacter*, of which five species have been recognised—*chroococcum*, *beijerinckii*, *vinelandii*, *agilis*[9]—which is probably only an aquatic form—and *indicum*. The first three appear to have very definite *p*H require-

[1] M. Roberg, *Jahrb. wiss. Bot.*, 1938, **86**, 344; O. von Plotho, *Arch. Mikrobiol.*, 1941, **12**, 1.
[2] M. C. Rayner, *Bot. Gaz.*, 1922, **73**, 226; W. N. Jones and M. L. Smith, *Brit. J. Expt. Biol.*, 1929, **6**, 167.
[3] R. Brown, *J. Agric. Sci.*, 1933, **23**, 527.
[4] *J. Agric. Sci.*, 1905, **1**, 280.
[5] N. R. Dhar, *J. Indian Chem. Soc., Indust. Ed.*, 1942, **5**, 210; *Nature*, 1943, **151**, 590.
[6] E. McCoy, W. M. Higby and E. B. Fred, *Zbl. Bakt.* II, 1928, **76**, 314; E. D. Rosenblum and P. W. Wilson, *J. Bact.*, 1949, **57**, 413.
[7] G. Bredemann, *Zbl. Bakt.* II, 1909, **23**, 385.
[8] S. A. Waksman, *Principles of Soil Microbiology*, 2nd ed., Baltimore, 1932.
[9] S. Winogradsky (*Ann. Inst. Pasteur*, 1938, **60**, 351) has suggested that this differs sufficiently from the other members of this group to be put in a new genus *Azomonas*.

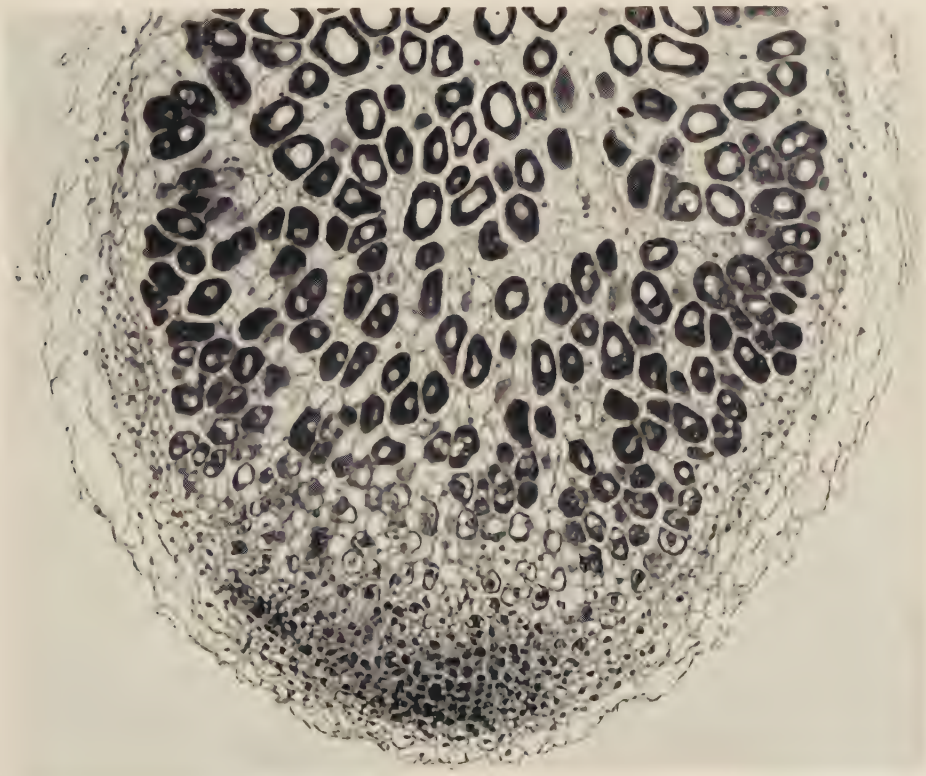
Healthy nodules on lucerne rootlets (natural size)
(*p. 311*)

A very young nodule on a lucerne rootlet seen by transmitted light. The dark lines across the centre of the rootlet are the vascular bundles (x 250)

(*p. 311*)

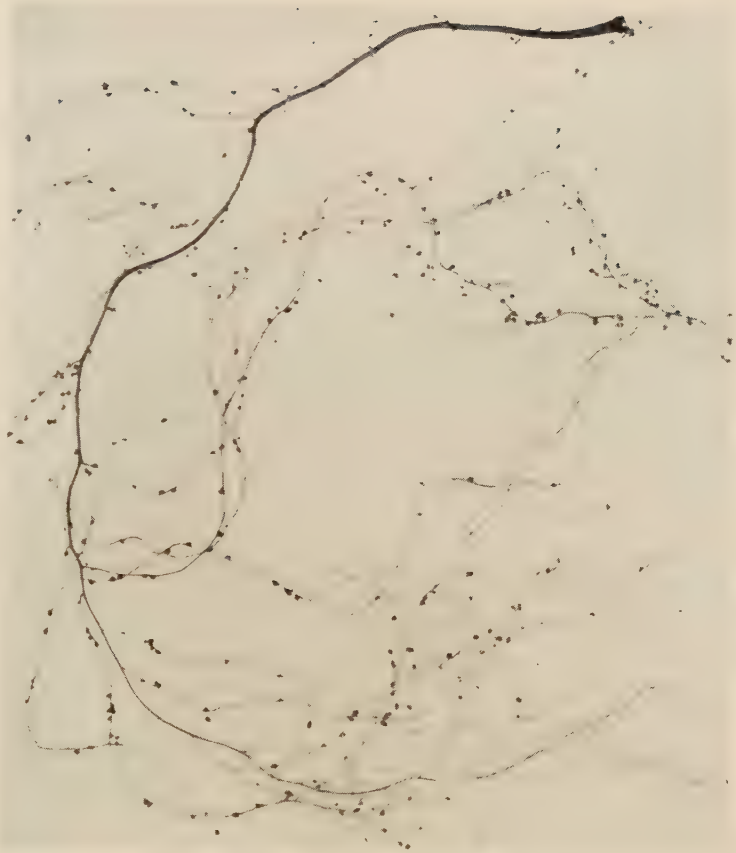


The nodule bacteria inside the cells of a clover rootlet. The black areas in some cells are their nuclei (x 1,500)



Transverse section of the meristematic end of a nodule. Note the cells filled with bacteria (x 180)

(*p. 317*)



Nodules formed by an ineffective strain (Coryn Strain) of the nodule bacteria on red clover roots

Nodules formed by an effective strain (Strain A) of the nodule bacteria on red clover roots

(*p. 311*)

ments, not being found in soils below *p*H 6,[1] whilst the last has been found in soils at *p*H 4·5 in Dacca in India and in Burma,[2] and R. A. Altson[3] appears to have found the same organism in Malaya. The conditions under which this organism lives in acid soils are not, however, understood, for H. Katznelson[4] found that it would not grow in acid New Jersey soils of *p*H 4·3 or 5·1, but would survive if lime was added; though H. L. Jensen[5] found it would fix nitrogen actively in the absence of calcium; (3) some blue-green algae of the family Nostococcaceae, which have already been described on p. 163.

Several other groups of bacteria, and some fungal genera, may possess this power;[6] and it is becoming increasingly desirable that these claims should be reinvestigated, using culture media containing the appropriate growth-promoting factors and minerals, and using air enriched with either heavy nitrogen N^{15}, or radioactive nitrogen N^{13}, which allows nitrogen fixation to be determined with much greater certainty than hitherto;[7] for until these claims have been disproved it is possible that in some soils the nitrogen supply is maintained by organisms other than those now recognised as nitrogen fixers.[8]

The chemistry of the nitrogen fixation process is still not known. The three organisms that have been investigated in detail—blue-green algae, *Azotobacter* and the nodule bacteria—may all use the same process. All three use an enzyme reaction that is suppressed in the presence of carbon monoxide or hydrogen gas,[9] and all three, as well as the nitrogen-fixing *Clostridia*, only fix nitrogen if supplied with small quantities of molybdenum,[10] though larger quantities of vanadium may possibly allow the enzyme to work much less efficiently. Neither *Azotobacter* nor blue-green algae fix nitrogen if supplied with nitrates or ammonia.[11] The first product of nitrogen fixation is not known for certain, but presumptive evidence is that it is ammonia which then reacts with α-keto-glutaric acid to give glutamic acid.[12]

[1] P. L. Gainey, *J. Agric. Res.*, 1923, **24**, 907.
[2] R. L. Starkey and P. K. De, *Soil Sci.*, 1939, **47**, 329. [3] *J. Agric. Sci.*, 1936, **26**, 268.
[4] *Soil Sci.*, 1940, **49**, 21. [5] *Proc. Linn. Soc., N.S.W.*, 1947, **78**, 299.
[6] See G. Senn, *Biol. Rev.*, 1928, **3**, 77, and T. R. Bhaskaran and S. C. Pillai, *Indian J. Agric. Sci.*, 1942, **12**, 178, for reviews. H. Frei (*Zbl. Bakt.* II, 1942, **104**, 326) considers some yeasts can fix nitrogen.
[7] See R. H. Burris *et al.*, *J. Biol. Chem.*, 1943, **148**, 349, for an example.
[8] For a critical discussion of the claims made that certain organisms and plants can fix nitrogen, see R. H. Burris and P. W. Wilson, *Ann. Rev. Biochem.*, 1945, **14**, 685.
[9] P. W. Wilson and R. H. Burris, *J. Bact.*, 1944, **47**, 410.
[10] H. Bortels, *Arch. Mikrobiol.*, 1930, **1**, 333; 1940, **11**, 155; *Zbl. Bakt.* II, 1933, **87**, 476; 1936, **95**, 193. For a review of work on this subject, see D. Burk and R. H. Burris, *Ann. Rev. Biochem.*, 1941, **10**, 587. For *Clostridia*, see H. L. Jensen, *Fourth Int. Congr. Microbiol.*, Copenhagen, 1947, 151, and with D. Spencer, *Proc. Linn. Soc., N.S.W.*, 1947, **72**, 73.
[11] For blue-green algae, see G. E. Fogg, *J. Expt. Biol.*, 1942, **19**, 78.
[12] For a review of the present position, see R. H. Burris and P. W. Wilson, *Ann. Rev. Biochem.*, 1945, **14**, 685; *Bact. Rev.*, 1947, **11**, 41; A. I. Virtanen, *Ann. Rev. Microbiol.*, 1948, **2**, 485.

Non-symbiotic Nitrogen Fixation in Soils

The amount of nitrogen fixed non-symbiotically is still undecided for many soils, because the possible fixation is only a small percentage of the total nitrogen in the soil, and many of the older methods for determining the total nitrogen in fact only determined part; so that if the total amount of nitrogen remained constant, but for any reason the proportion of nitrogen determined varied with the time of year, soil treatment, or other cause, the result would have been interpreted as showing either a loss or a gain of soil nitrogen.

Nitrogen-fixing organisms can be found in most soils, but usually in very small numbers. *Clostridia* appear to be more widespread than *Azotobacter* and to occur in rather large numbers, up to 1,000,000 per gm. being recorded, though the numbers are usually much lower; but not all these *Clostridia* necessarily possess any appreciable nitrogen-fixing power. *Azotobacter* rarely occur in soils below *p*H 6 though *Azotobacter indicum* forms an exception as it typically occurs in soils of *p*H 5 or less, and they are sensitive to phosphate deficiency. S. Winogradsky[1] and H. R. Christensen,[2] in fact, have used these organisms to measure phosphate deficiency in soils, and A. B. Beck[3] and H. L. Jensen[4] both found that only half of the East Australian wheat soils with *p*H 6 or above—which are all typically short of phosphate—contained *Azotobacter*, and of these only a few that had been made rich in humus contained more than 100 per gm. European soils generally contain about 2,000,[5] but may contain up to 20,000 or more per gm.

Under arid conditions, such as occur in the western states of the U.S.A., the numbers of *Azotobacter* tend to be very low if the rainfall is below 15 inches per year—unless the soil is irrigated—but to be fairly common if above 20 inches,[6] though their numbers in these soils may show slow fluctuations, being apparently absent for some years and then becoming common again. The nitrogen-fixing blue-green algae, although they also have a world-wide distribution, only seem to develop extensively enough to add an appreciable quantity of nitrogen to the soil in wet tropical or subtropical conditions, such as paddy fields or on bare soils after heavy rains. These specialised organisms, therefore, seem to be too rare to effect any appreciable nitrogen fixation under normal agricultural conditions.

The process of nitrogen fixation by *Azotobacter* has been extensively

[1] *Ann. Inst. Pasteur*, 1928, **42**, 36.
[2] *Soil Sci.*, 1923, **15**, 329.
[3] *Aust. J. Expt. Biol.*, 1935, **13**, 127.
[4] *Proc. Linn. Soc., N.S.W.*, 1940, **65**, 1.
[5] S. Winogradsky, *Ann. Inst. Pasteur*, 1928, **42**, 36.
[6] S. C. Vandecaveye and C. D. Moodie, *Proc. Soil Sci. Soc. Amer.*, 1943, **7**, 229.

studied, but all the work before 1935 cannot be properly interpreted, as the fundamental role of molybdenum in the process had not then been appreciated. *Azotobacter* has very definite nutritional needs: it can use as its source of energy some sugars and a number of simple organic compounds, particularly the lower fatty acids and simple aromatic acids such as benzoic, but it cannot use polymerised carbohydrates such as celluloses, starches or gums. It needs phosphates, calcium or strontium[1] and iron; it makes its most rapid growth with ammonia, or urea which it hydrolyses to ammonia, as its source of nitrogen; it grows well on nitrates, atmospheric nitrogen, or asparagin, and can make some growth on a few other amino acids,[2] but it needs traces of molybdenum to make maximum growth on sources other than ammonia or urea, the quantity needed depending on the nitrogen source, and is largest if it is fixing nitrogen.[3] Ammonia seems to be its most natural source of nitrogen, for the organism takes time to adapt itself to any other form after it has been using ammonia, but it can use ammonia directly after using any other source.[4]

The conditions under which *Azotobacter* will fix nitrogen in pure cultures are a readily utilisable source of energy, the requisite minerals, and a low concentration of readily utilisable nitrogen compounds: under these conditions it will fix up to 20 mgm. of nitrogen per gm. of sugar decomposed, or about 1 gm. of nitrogen per 20 of carbon used. Exchangeable calcium on clays is as readily available to the bacteria as soluble calcium.[5] The presence of ammonium ions depresses nitrogen fixation more strongly than does nitrate ions,[6] but for soils containing adequate molybdenum the normal equilibrium levels of ammonia and nitrate concentrations in the soil solution are probably too low to have any strong depressing action.

Azotobacter growing in pure culture may excrete into the medium 50 to 70 per cent of the total nitrogen it fixes, though very young cultures may not excrete more than 10 per cent. C. K. Horner and Dean Burk[7] showed that these excretions were protein-like substances of varying degrees of complexity, though for some strains up to 10 per cent might be ammoniacal. The excretion products are characteristic of rapidly growing colonies of *Azotobacter*, for they are produced in rather larger quantities if the bacteria are using ammonia, urea, nitrates, or asparagin as their source of nitrogen. It is uncertain,

[1] H. L. Jensen (*Proc. Linn. Soc., N.S.W.*, 1947, **72**, 299) considers that *Az. indicum* does not need calcium or strontium.
[2] P. W. Wilson and C. J. Lind, *J. Bact.*, 1943, **45**, 219.
[3] D. Burk and R. H. Burris, *Ann. Rev. Biochem.*, 1941, **10**, 587.
[4] R. H. Burris and P. W. Wilson, *J. Bact.*, 1946, **52**, 505.
[5] T. M. McCalla, *Soil Sci.*, 1939, **48**, 281.
[6] C. K. Horner and F. E. Allison, *J. Bact.*, 1944, **47**, 1.
[7] *Trans. 3rd Comm. Int. Soc. Soil Sci.*, New Brunswick, 1943, A, 168.

however, if this excretion takes place in soils, for Jensen[1] found that on adding glucose to some Australian wheat soils and incubating them under aerobic conditions, the amount of nitrogen fixed by the *Azotobacter* was approximately equal to the nitrogen content of their cells in the soil, strongly suggesting that under the competitive conditions existing in well-aerated soils very little of the nitrogen fixed is excreted.

Azotobacter will grow symbiotically with facultative anaerobes under partially anaerobic conditions on plant residues, such as cellulose, hay or straw, in the absence of added nitrogen but in the presence of nitrogen gas; there must be an air supply, but it must be sufficiently restricted so that the fermenting bacteria convert a considerable proportion of the cellulose, etc., they break down into simple acids, such as lactic, butyric or acetic.[2] Thus, under water-logged conditions, H. L. Jensen and R. J. Swaby[3] found that *Azotobacter* could fix about 14 mgm. of nitrogen per gm. of cellulose decomposed, and most of this nitrogen was taken up by the other bacteria. C. J. Lind and P. W. Wilson[4] also found that under these symbiotic conditions *Azotobacter* could fix nitrogen efficiently with a much more restricted supply of available iron than in pure culture.

The soil conditions favouring non-symbiotic nitrogen fixation conform to expectations based on these results, for this nitrogen fixation only seems to be an important factor in the nitrogen economy of two types of agricultural soils: those receiving appreciable dressings of decomposable material low in nitrogen, e.g. sugar or cellulose, and those carrying an obvious development of blue-green algae. The addition of carbohydrates always reduces the level of nitrates and ammonia in the soil, but it does not necessarily lead to any fixation of nitrogen. Table 71, taken from some pot experiments of A. Koch,[5] gives an example of the addition of glucose and sucrose to a soil leading to nitrogen fixation: the first effect of the sugars was that the oat crop sown shortly after the sugar had been added was depressed, owing to shortage of available nitrogen for the plant, but in the following spring the effect of the sugar was clearly seen in the increased nitrogen content of the soil, and this was reflected in the yield of sugar-beet taken that year.

Semi-arid wheat soils have often been suspected of possessing the power of fixing nitrogen, for some of them have now carried a large number of wheat crops without the yield showing any systematic decrease, and it has been suggested that the soil must be fixing nitrogen

[1] *Proc. Linn. Soc., N.S.W.*, 1940, **65**, 1. [2] E. H. Richards, *J. Agric. Sci.*, 1939, **29**, 302.
[3] *Proc. Linn. Soc., N.S.W.*, 1941, **66**, 89. [4] *Soil Sci.*, 1942, **54**, 102.
[5] *J. Landw.*, 1907, **55**, 355.

TABLE 71

Effect of Glucose and Sucrose on the Productiveness and Nitrogen Content of the Soil

Sugar added per 100 gm. of soil	Crops obtained				Total N removed in both crops	Nitrogen left in soil, Spring 1906	
	Oats, 1905		Sugar-beet, 1906				
	Dry matter	Yield of N	Dry matter	Yield of N	Gm.	Total N per cent	N as nitrate, parts per million
None . . .	100	100	100	100	0·591	0·093	10
2 gm. glucose . .	32·8	62·5	186	190	0·681	0·105	17
2 gm. sucrose . .	33·3	58·7	179	195	0·680	0·105	15
4 gm. sucrose . .	37·7	78·1	283	339	1·099	0·119	37

to replace that taken away in the wheat. H. L. Jensen[1] has recently studied this problem very carefully for some East Australian wheat soils. In the first place, he estimates the loss of nitrogen on soils carrying a 12-bushel crop every second year at about $5\frac{1}{2}$ lb. per acre per year, which would correspond to the amount of nitrogen in nearly 100 lb. of organic matter. He found, however, that these soils had no power of fixing nitrogen unless organic matter was added, and even then only a few possessed it; that a very high population of *Azotobacter* was necessary for fixation, but in some soils high populations did not bring about any; and that adding cellulose, straw or hay caused only very small fixations of nitrogen unless the soil was so wet that partially anaerobic conditions set in, and even under these very favourable conditions all the straw, stubble and roots of the preceding wheat crop only allowed the *Azotobacter* to fix one-third of the nitrogen removed in the grain. Thus, for these Australian wheat soils there is no evidence that non-symbiotic nitrogen fixation plays any significant role, and this conclusion is in accord with many other experiments made elsewhere. There is, however, some American evidence that it may take place in semi-arid fallow soils under some conditions. Thus J. S. Burd and J. C. Martin,[2] in California, and J. E. Greaves and L. W. Jones,[3] in Utah, found it operative if the soil's moisture content was not too high. There also remains the possibility that it is a factor helping to stabilise the nitrogen content of the soil around its equilibrium value for the

[1] *Proc. Linn. Soc., N.S.W.*, 1940, **65**, 1. This paper contains a long and critical review of the literature on non-symbiotic nitrogen fixation.

[2] *Hilgardia*, 1931, **5**, 455.

[3] *Soil Sci.*, 1942, **53**, 229.

vegetation or rotation that the soil is carrying, and that it will come into prominence, provided the soil conditions are suitable, whenever the vegetation or crop rotation is altered in such a direction that the new nitrogen equilibrium level is higher than the old.[1]

The conclusions reached from all the work that has been done on *Azotobacter* and other non-symbiotic nitrogen fixers is that so far there is very little evidence that they are of any practical importance on normal temperate arable soils, though H. Bortels[2] believes this is often due to too low a level of molybdenum in the soil, and has claimed some spectacular increases in the nitrogen content of some soils simply by adding sodium molybdate to them. On grassland containing legumes it is not possible to separate out any possible fixation by non-symbiotic nitrogen fixers from the symbiotic nitrogen fixation, though the non-symbiotic bacteria may be of importance. Thus, T. L. Lyon and H. O. Buckman,[3] at Ithaca, found the soil under a grass ley apparently free from legumes accumulated 40 lb. of nitrogen per acre per year if the ley was cut and the grass left on the surface, but lost a few pounds if the hay, which contained about 20 lb. of nitrogen per year, was removed. Similarly, J. W. White, F. J. Holben and A. C. Richer,[4] working in Pennsylvania, found the soil under a grass ley described as free from leguminous plants, gained 15 to 30 lb. of nitrogen per year even though they were unable to isolate *Azotobacter* from the soil. In woodlands, conditions for non-symbiotic nitrogen fixation should again be ideal, although this does not seem to have been made the subject of any critical research. This is the probable mechanism for the increase in soil nitrogen in Geescroft, given in Table 70, for here conditions should be very favourable for the development of *Azotobacter* and *Clostridia*—a good supply of calcium carbonate and of coarse grass herbage low in nitrogen and extended periods throughout the year when partially anaerobic conditions prevail.

Various claims have been made that the nitrogen economy of a soil can be improved by suitably inoculating it with *Azotobacter*, without adding any additional energy-containing material. This is an unexpected result if true, for except under special circumstances, it is very improbable that a specially introduced soil bacterium could establish itself in appreciable numbers in competition with the local soil microbial population. Thus A. Dunez,[5] who claims that if the seed of crops are inoculated with a mixture of *Azotobacter* and a blue-green alga, and if at the same time certain growth-promoting substances of the indolyl

[1] H. V. Smith, *Arizona Agric. Expt. Sta., Tech. Bull.* 102, 1944, gives a possible example of this effect.

[2] *Arch. Mikrobiol.*, 1937, **8**, 1.

[3] *The Nature and Properties of Soils*, 4th ed., New York, 1943, p. 393.

[4] *J. Amer. Soc. Agron.*, 1945, **37**, 21. [5] *C.R. Acad. Agric.*, 1946, **32**, 736; 1947, **33**, 548.

acetic acid and vitamin B type are added, crop growth is improved very considerably. B. N. Uppal and his co-workers[1] claim that the root excretions of seedling radish and rice plants growing in water culture, and of radish, rice, wheat and sorghum growing in water culture to which sterile soil is added, enable *Azotobacter* to fix up to eight times as much nitrogen as the *Azotobacter* growing in the absence of these roots. A. Starc[2] found that maize roots increase the numbers of *Azotobacter* in the soil and the amount of nitrogen they fix although they do not multiply in the rhizosphere nor does the maize benefit from the nitrogen fixed. F. E. Allison[3] has recently reviewed the literature about many of these claims, but was unable to confirm any of them in greenhouse experiments,[4] and F. E. Clark[5] was unable to confirm them in field experiments.

Symbiotic Nitrogen Fixation in Leguminous Plants

Most species of leguminous plants carry nodules on their roots when growing in natural conditions, as is shown for lucerne in Plate XIII and for clover in Plate XVI, and these nodules are the seat of the main nitrogen-fixing process of agricultural importance in temperate and probably also tropical regions. They contain bacteria living symbiotically with the plant, the plant leaves supplying the carbohydrates and the bacteria the nitrogen for the combined organism. But the bacteria become parasitic if for any reason the carbohydrate supply is restricted, as, for example, by keeping the plant in the dark,[6] or by restricting the boron supply[7] so that the vascular strands supplying carbohydrates to the nodule fail to develop, for the nodules form close to the vascular strands, as can be seen in Plate XIV. This parasitism also occurs normally in old nodules, resulting in their decay.

The biochemistry of the nodule is only partially understood, the great experimental difficulty being that the bacteria can so far only be made to fix nitrogen when living in the nodule—possibly only in a nodule attached to a growing plant.[8] They can, however, easily be grown in simple culture media, though some species need biotin and some aneurin and possibly other similar growth-promoting factors[9] for

[1] *Proc. Indian Acad. Sci.*, 1947, **25** B, 173. [2] *Arch. Mikrobiol.*, 1942, **13**, 164.
[3] *Soil Sci.*, 1947, **64**, 413. [4] *Soil Sci.*, 1947, **64**, 489. [5] *Soil Sci.*, 1948, **65**, 193.
[6] H. G. Thornton, *Proc. Roy. Soc.*, 1930, **106** B, 110.
[7] W. E. Brenchley and H. G. Thornton, *Proc. Roy. Soc.*, 1925, **98** B, 373.
[8] A. I. Virtanen, *Suomen Kemist*, 1937, **10** B, 24; *Trans. 3rd Comm. Int. Soc. Soil Sci.*, New Brunswick, 1939, A, 4, claimed that excised and crushed nodules supplied with oxalacetic acid can fix nitrogen, but neither P. W. Wilson (*Ergebn. Enzymforsch.*, 1939, **8**, 13) nor F. E. Allison (*Bot. Gaz.*, 1942, **104**, 63) could confirm this result.
[9] R. Nilson, G. Bjalfve and D. Burström, *LantbrHögsk. Ann.*, 1939, **7**, 302; F. E. Allison and F. W. Minor, *Proc. 3rd Int. Congr. Microbiol.*, New York, 1939, 486.

active growth. The chemistry of nitrogen fixation must, therefore, be different in the symbiotic and non-symbiotic organisms, although one, or a group, of the enzymes involved appears to be similar. This is the one that is inactivated by carbon monoxide and hydrogen and contains molybdenum, presumably in the prosthetic group. Symbiotic fixation, however, differs from non-symbiotic in that haemoglobin appears to play an essential role in the process, for active nodules are rich in this pigment.[1] Its occurrence is of great theoretical interest—it needs both the bacteria and the plant for its production—because haemoglobin is characteristic of the vertebrates and is not found in micro-organisms or plants, with this exception, although it has been recorded in the protozoa *Paramœcium.*

The nodules also need an adequate supply of calcium and phosphate as well as molybdenum for nitrogen fixation. The calcium supply seems to limit the nitrogen fixing power of nodules in acid soil, for many legumes, peas and clovers, for example, can grow in soils too acid for their nodules to fix any nitrogen. Thus, A. I. Virtanen[2] found they could grow in soils of *p*H 4 if supplied with available nitrogen, but could not fix any nitrogen unless the *p*H was at least 5, though Jensen[3] found that subterranean clover could still fix nitrogen in soil of *p*H 4·2–4·5 although at a slower rate than it could at a higher *p*H. W. A. Albrecht[4] has recently re-emphasised the role of calcium, as distinct from acidity, in encouraging nodulation, and has even been able to obtain excellent nitrogen fixation by soybeans growing in a soil of *p*H 4·2 adequately supplied with calcium.

Leguminous plants, however, seem to differ very considerably among themselves in their calcium requirements for efficient nitrogen fixation. Thus, lupins appear to grow and to fix nitrogen in very acid soils, and white clover, and possibly also red, grow and fix nitrogen well on soils too acid for lucerne and related plants to be efficient nitrogen fixers.[5] The interpretation of this variable sensitivity to acidity is not known; it may lie in the different powers the various roots possess of extracting calcium from the soil, but this has not been tested.

The molybdenum requirements of leguminous plants are entirely, or almost entirely, for the nitrogen-fixing mechanism; for the plants will grow perfectly well, and their roots will be well nodulated, in soils

[1] H. Kubo, *Acta Phytochim., Tokyo*, 1939, **11**, 195; D. Keilin with Y. L. Wang, *Nature*, 1945, **155**, 227; with J. D. Smith, ibid., 1947, **159**, 692; A. I. Virtanen with T. Laine, ibid., 1946, **157**, 25; *Biol. Rev.*, 1947, **22**, 239.

[2] *Biochem. Ztschr.*, 1928, **193**, 300.

[3] *Proc. Linn. Soc., N.S.W.*, 1947, **72**, 265.

[4] *J. Amer. Soc. Agron.*, 1933, **25**, 512; with C. B. Harston, *Proc. Soil Sci. Soc. Amer.*, 1942, **7**, 247.

[5] For examples of this, see H. L. Jensen, *Proc. Linn. Soc., N.S.W.*, 1944, **69**, 229; 1947, **72**, 265; *Aust. J. Sci.*, 1946, **9**, 118.

very low in molybdenum, but the nodules will fix no nitrogen.[1] Again, if the molybdenum is in short supply, the molybdenum in the plant will be concentrated in the nodules rather than in the roots or tops. Thus H. L. Jensen and R. C. Betty[2] found the nodules contained 6–20 parts of molybdenum per million of dry matter, which was 5–15 times as much as the rest of the root system, which in turn had a higher content than the tops. It is only when the supply is adequate that the molybdenum content of the tops begins to rise. In Australia there are some soils on which clovers will not grow unless they are given a dressing of a molybdenum salt, but the dressing is of the order of a few ounces of sodium molybdate per acre.[3] If the concentration of molybdenum in the soil is too high, it accumulates in the leaves of the leguminous plants and causes the soil to become "teart"[4] (see p. 56).

The bacteria in the nodules need to be supplied with energy, if they are to fix nitrogen; P. W. Wilson[5] has estimated this at about 20 lb. of carbohydrate for each pound of nitrogen fixed, or about 80 kg. cals. per gm. of nitrogen fixed, which corresponds to an efficiency about 2½ times that of *Azotobacter* and *Clostridia*. This supply of carbohydrates to the nodule has the consequence that the respiration of a nodulated root will be much higher than a normal root, which explains the field observation that soils carrying legumes respire up to twice as much carbon dioxide as those carrying cereal or root crops, as shown in Table 76 on page 337.[6] Wilson's figures give, for a nitrogen fixation of 150 lb. per acre in 150 days of summer, a carbon dioxide production of 3·3 gm. per sq. m. per day, a figure that should be compared with normal rates of soil respiration given in Table 76.

The bacteria can be very active fixers of nitrogen. Thus Jensen[7] found that when lucerne is growing under good conditions, up to 100 milligrams of nitrogen can be fixed daily by each gram of dry matter in the nodule, which corresponds to 1·36 times its own nitrogen content, and up to 50 milligrams can be fixed by the nodules of subterranean clover, though for each crop the average fixation per unit of dry matter in the nodules is usually about half of these rates. He further found that, for these rates to be possible, the lucerne nodules must contain 10–25 p.p.m. of molybdenum and the clover 4–8 p.p.m. in the dry nodule tissue.

[1] A. J. Anderson, *Aust. Counc. Sci. Indust. Res., Bull.* 198, 1946; H. L. Jensen, *Proc. Linn. Soc., N.S.W.*, 1945, **70**, 203.

[2] *Proc. Linn. Soc., N.S.W.*, 1943, **68**, 1. See also K. G. Vinogradova, *C.R. Acad. Sci. (U.S.S.R.)*, 1943, **40**, 26.

[3] H. C. Trumble and H. M. Ferres, *J. Aust. Inst. Agric. Sci.*, 1946, **12**, 32.

[4] For the margin between optimum molybdenum contents for nitrogen fixation and the minimum for teartness, see H. L. Jensen, *Proc. Linn. Soc., N.S.W.*, 1946, **70**, 203.

[5] *The Biochemistry of Non-symbiotic Nitrogen Fixation*, Madison, 1940.

[6] E. Reinau, *Fortschr. Landw.*, 1926, **1**, 787.

[7] *Proc. Linn. Soc., N.S.W.*, 1947, **72**, 265.

The nodule bacteria are now referred to as the genus *Rhizobium*, though they were formerly called *Bacillus radicicola*. They resemble in many characteristics the typical soil bacterium *Achromobacter radiobacter*, which is often found near the roots of plants, particularly of legumes, and also *Phytomonas tumefaciens*, which may be parasitic on plant roots, producing swellings or tumours on them.[1] The bacteria exist in a number of species or strains which differ both in their serological reactions[2] and in their leguminous host plants, and unfortunately there is no very close correlation between the variations in these two reactions. Thus, typical nodules on red clover can be produced by several serologically unrelated groups of bacteria. These can form nodules on most other species of *Trifolium*, but not on plants of unrelated genera such as peas or lucerne. Yet other bacteria can form nodules on peas, but not on red clover, that are closely related serologically to some of the red clover bacteria.[3] The nodule bacteria can be classified by other characteristics besides these two, but again these classifications cut across the divisions produced by either of the other two. There are, therefore, at the present time, no accepted criteria for deciding how to divide these bacteria up into distinct named species.

The nodule bacteria have in general been divided into groups according to the host plant they infect. E. B. Fred and his Wisconsin co-workers[4] have developed this method and divided the bacteria up into a number of cross-inoculation groups to which they have given specific names. The most important of these groups are:

1. Lucerne and sweet clover (*Medicago* and *Melilotus*).
2. Clovers (*Trifolium*).
3. Pea and vetch (*Pisum*, *Lathyrus*, *Vicia*, *Lens*).
4. Soybean (*Glycine*).
5. Lupin and serradella (*Lupinus*, *Ornithopus*).
6. A few species of *Phaseolus*—*vulgaris*, *coccineus* and *angustifolia*.
7. A large ill-defined group containing most other crop legumes, such as cow-peas, groundnut, lespedeza, and the remaining species of *Phaseolus*.

This classification is only valid in a general sense. The last group is certainly ill-defined, and there are bacteria that infect members of more than one group. Thus, J. Kleczkowska, P. S. Nutman and G. Bond[5] have found bacteria in English soils that will infect both peas

[1] For a discussion of the interrelationships of these groups, see H. J. Conn, G. E. Wolfe and M. Ford, *J. Bact.*, 1940, **39**, 207; 1942, **44**, 353.

[2] D. Q. Hughes and J. M. Vincent, *Proc. Linn. Soc., N.S.W.*, 1942, **47**, 142.

[3] A. Kleczkowski and H. G. Thornton, *J. Bact.*, 1944, **48**, 661.

[4] E. B. Fred, I. L. Baldwin and E. McCoy, *Root Nodule Bacteria and Leguminous Plants*, Madison, 1932. This monograph gives an excellent summary of the literature up to this date.

[5] *J. Bact.*, 1944, **48**, 673.

and clovers, and J. K. Wilson[1] has found many strains that will infect legumes from several of these groups; he, in fact, prefers to group the legumes into classes ranging from those that can be infected by a very large proportion of the bacterial strains, through those that can only be infected by a few, to those that cannot be infected by any, and therefore carry no nodules.

This ability of a strain to form nodules on a plant does not necessarily render it agriculturally useful, for this only happens if the nodules fix appreciable amounts of nitrogen. Strains that produce such nodules are called effective, to distinguish them from the ineffective strains which produce nodules that only fix much smaller amounts of nitrogen. It is possible that a given bacterial strain can only be effective on plants in one of Fred's groups, even if it can give rise to nodules on plants in another; and certainly within its own normal host plant group it may be effective on some species and not on others.

These distinct but related questions of strain specificity and strain effectiveness are of great agricultural importance, for leguminous crops can only be profitably grown on a soil if suitable strains of effective bacteria are present. Thus the cultivation of lucerne in England used to be limited to the few soils that contained the appropriate bacteria.

Suitable bacteria can be introduced into a soil in two ways: the land can be dressed with soil from a field where the crop has recently been grown successfully, or the bacteria in pure culture can be mixed and drilled in with the seed, and this latter is the method that has been most widely developed and successfully used in recent years. The nodule bacteria, once established in a soil, can live there many years without any host legume being grown. The indigenous strains seem to be very long-lived, and introduced strains can probably live for at least ten years in the field.[2] They therefore apparently form the exception to the rule that introduced species of soil-inhabiting bacteria cannot compete with the indigenous soil inhabitants unless the soil conditions are altered in their favour. This happens whilst the leguminous plant is growing, but the introduced bacteria continue to exist along with the indigenous population for many years after the leguminous plants have ceased to be present.

Nodule bacteria, when living in the soil, can be attacked by several strains of bacteriophage, but the individual phage strain can only attack its own characteristic group of nodule bacteria which often consists of bacterial strains from more than one of the Wisconsin cross-inoculation groups. The typical method of attack is that the phage lyses most members of the susceptible bacteria, but usually a few are

[1] *J. Amer. Soc. Agron.*, 1939, **31**, 159; *Cornell Agric. Expt. Sta., Mem.* 221, 1939; *Soil Sci.*, 1944, **58**, 61.

[2] A. L. Whiting, *J. Amer. Soc. Agron.*, 1925, **17**, 474.

left unlysed:[1] these produce a secondary growth of bacteria resistant to the particular phage if the cultures are kept long enough. They may show other differences from the original strain, sometimes being converted from an ineffective mutant back to the original effective strain.

These phages have been assumed to be a cause of clover and lucerne sickness[2] in soils, but there is little positive evidence for this assumption; indeed, J. Kleczkowska has recently shown that pea-bacterial phages occur in soils giving no sign of pea sickness, and also that the unknown cause of clover sickness can be removed much more easily than phages from soils.

The need for soil inoculation stimulated research on the way these bacteria live in the soil and enter the plant. The organism can take a number of forms; it may be rod-shaped or coccoid, and these may develop one or more flagellae, in which case they can move at about one inch every two to three days under normal conditions.[3] The proportion that is motile increases with the phosphate supply,[4] and hence this must be adequate for maximum infection to take place. When the plant is ready to be infected, which is usually after the first true leaf has opened,[5] it secretes a substance from its roots which stimulates the multiplication of these bacteria and related species, such as *Achromobacter radiobacter*, around it.[6] The nodule bacteria in turn secrete a substance, probably β-indolyl acetic acid,[7] which causes a root hair in their immediate neighbourhood to curl over; it is in this curled region that the bacteria enter the root hair, move into certain cortical roots cells and stimulate their division, so forming a nodule. Only a small fraction of the root hairs ever become infected, and of these only a small fraction lead to a nodule. E. McCoy,[8] for example, found on some six-weeks-old lucerne plants that only 5 per cent of the root hairs were infected, and under 2 per cent of those infected led to the formation of a nodule. The reasons for these low percentages are not definitely known, though L. Wipf and D. C. Cooper[9] have claimed that the bacteria must infect a tetraploid cell if a nodule is to be formed. A tetraploid cell has twice the number of chromosomes of a normal cell, and Wipf and Cooper observed that the multiplying cells in young nodules were tetraploid, and that tetraploid cells were scattered throughout uninfected cortical cells of the root: it is only

[1] J. Kleczkowska, *J. Bact.*, 1945, **50**, 71, 81; 1946, **52**, 25.
[2] A. Demolon and A. Dunez, *C.R.*, 1933, **197**, 1344; 1934, **199**, 1257; *Ann. Agron.*, 1935, **5**, 89.
[3] K. F. Kellerman and E. H. Fawcett, *Science*, 1907, **25**, 806. See also W. C. Frazier and E. B. Fred, *Soil Sci.*, 1922, **14**, 29.
[4] H. G. Thornton and N. Gangulee, *Proc. Roy. Soc.*, 1926, **99** B, 427.
[5] H. G. Thornton, *Proc. Roy. Soc.*, 1929, **104** B, 481.
[6] H. Nicol and H. G. Thornton, *Proc. Roy. Soc.*, 1941, **130** B, 32.
[7] K. V. Thiman, *Proc. Natl. Acad. Sci. Wash.*, 1936, **22**, 511; *Trans. 3rd Comm. Int. Soc. Soil Sci.*, New Brunswick, A, 1939, 24; H. K. Chen, *Nature*, 1938, **142**, 753.
[8] *Proc. Roy. Soc.*, 1932, **110** B, 514.
[9] *Amer. J. Bot.*, 1940, **27**, 821.

when an infected root hair happens to be near to a tetraploid cortical cell that a nodule is formed on this theory.

The mature nodule consists of a cap of uninfected cortical cells, behind which is a region of rapidly dividing uninfected cells, and behind these are the much larger cells filled with rhizobial bacteria. It is these cells that Wipf considers to be tetraploid. The recently infected cells contain rods and coccoid forms, whereas the older cells contain the banded "bacteroids", which are rod-shaped cells that stain in bands. These stages are illustrated in Plate XV. As the nodule ages the cells and nodule bacteria lose their ability to divide, a large vacuole appears which crowds the invading organisms and cell contents into a dense mass around the periphery of the cell wall, and finally the bacteria digest the remaining cell contents and attack the cell wall—the nodule becomes necrotic and sloughs off, and the bacteria are released into the soil.

The period in the plant's growth when nodules are formed depends on the plant. The majority of nodules on annual crops, such as peas or soybeans, form during a period of one or two weeks, whilst in perennial crops, such as clovers, new nodules are forming throughout most of the growing season, though they are annual growths, being shed every autumn.

The process of infection and nodule formation can be disturbed if the nitrate or ammonium concentration around the plant roots is too high. A high nitrate concentration reduces the proportion of root hairs that can be infected, though this reduction can in part be counteracted by adding a suitable quantity of glucose to the solution.[1] Nitrate not only reduces the number of nodules, it also decreases their volume. The volume can, in fact, be halved by a concentration of nitrate insufficient to affect the number of nodules.[2]

A legume root can carry nodules formed by several bacterial strains, though each nodule carries a pure culture of a strain and is free from bacteriophage. The root can normally only carry a limited number of nodules per unit length; hence, if root growth ceases fairly early in the season, as it may do with peas, for example, the root system can become saturated with nodules, and once this has happened no further bacteria of any other strain can produce additional nodules on the root. Root saturation will not be shown by plants such as clovers whose root system continues to develop through much of the growing season.

The strain of bacteria that produces a nodule affects its size and longevity and the amount of nitrogen it can fix. Effective strains

[1] H. G. Thornton, *Proc. Roy. Soc.*, 1936, **119** B, 474.
[2] H. G. Thornton and H. Nicol, *J. Agric. Sci.*, 1936, **26**, 173.

normally produce fewer and larger nodules than ineffective strains, as is shown in Plate XVI for clover.[1] Ineffectiveness of a strain does not necessarily appear to be due to any defect in the nitrogen-fixing mechanism of the symbiosis, but rather to imperfect adaptation of the plant to the bacteria, for nodules produced by many ineffective strains fix as much nitrogen as those produced by effective strains, if measured on the basis of equal volumes of nodule and equal times,[2] but they remain small and are short-lived,[3] implying that the plant cells react to an ineffective strain by producing some substance that inhibits nodule growth. However, A. I. Virtanen[4] has claimed to have isolated strains of bacteria that can form nodules, but are quite unable to fix any nitrogen or to produce the necessary haemoglobin in the nodule. Thus, he considers there are all gradations in the symbiosis between the rhizobial bacteria and the plant.

The effectiveness of one strain of bacteria compared with another may depend on both the plant species and the variety within the species. Thus, some bacteria are effective on nearly all species of *Medicago* and *Melilotus*, some are effective on only one or two wild species, but not on the cultivated, whilst others are effective on some varieties of lucerne, but not on others.[5] Indeed, the effectiveness of a given bacterial strain for a given variety of host plant may depend on one of the genes in the plant, and these genes show very marked specificity for individual bacterial strains.[6]

Effectiveness of a given strain for a certain host plant is not a very stable property. An effective strain, inoculated into certain soils, will produce an ineffective mutant,[7] and nothing is known about what soil conditions encourage the growth of the mutant at the expense of the original form. No case has yet been found of an ineffective strain producing a more effective mutant, though an ineffective mutant of a previously effective strain may once again mutate into the original effective strain under the influence of a bacteriophage and under other unanalysed soil conditions.

Soils may contain more than one strain of nodule bacteria for a given host, so that the numbers of nodules formed by each strain will depend on the numbers of each strain present in the soil, their rate of multiplication outside the root hair, and their power of infecting a root hair and causing a nodule to form. H. Nicol and H. G. Thornton[8] showed

[1] J. T. Kroulik and P. L. Gainey, *J. Agric. Res.*, 1941, **62**, 359.
[2] H. K. Chen and H. G. Thornton, *Proc. Roy. Soc.*, 1940, **129 B**, 208.
[3] H. K. Chen, H. Nicol and H. G. Thornton, *Proc. Roy. Soc.*, 1940, **129 B**, 475.
[4] *Biol. Rev.*, 1947, **22**, 239.
[5] P. W. Wilson, J. C. Burton and V. S. Bond, *J. Agric. Res.*, 1937, **55**, 619; *Soil Sci.*, 1939, **47**, 293. For soybeans, see J. Boyes and G. Bond, *Ann. Appl. Biol.*, 1942, **29**, 103.
[6] P. S. Nutman, *Nature*, 1946, **157**, 463.
[7] P. S. Nutman, *J. Bact.*, 1946, **51**, 411.
[8] *Proc. Roy. Soc.*, 1941, **130 B**, 32.

that in mixed cultures the proportion of nodules formed by each type of bacteria is affected by their relative rates of multiplication outside the root hair: one strain will form nearly all the nodules if it grows appreciably faster than another. This property of strain dominance is independent of the infectivity of the strain, that is, on the number of nodules formed per unit length of root, and also of its effectiveness: dominance, infectivity and effectiveness are, in fact, three independent properties of a strain.

Ineffective strains of nodule bacteria are abundant in some soils. Thus, H. G. Thornton[1] finds that they produce 30 per cent of the nodules on the roots of white clover in the hill districts of the west and north of Great Britain, and they may be an important factor limiting the establishment of clovers in these areas. The problem of counteracting this harmful effect is difficult, as it is in just such soils that effective bacterial strains are apt to produce ineffective mutants, so that if the problems of inoculation of the soil with an effective strain are soluble, one has to find strains that are not only effective but stable. The problem of inoculation is more complicated when one is trying to replace a strain that is indigenous in the soil with one that is introduced. For the introduced strain must be present in far smaller numbers than the indigenous with which it must compete just outside the plant roots. Fortunately, strains vary in their powers of competition one with another, and it is sometimes possible to find strains that possess the three desirable qualities of effectiveness, genetic stability and power to compete successfully with the indigenous strains.

The amount of nitrogen fixed by a leguminous plant depends not only on the quality of the bacterial strain present, but also on external conditions. Adequate supplies of calcium and phosphate are essential for good growth and good fixation, and on some soils potassium and molybdenum also may be needed. W. A. Albrecht's work[2] in Missouri with soybeans suggests that a low ratio of available potassium to available calcium is desirable, but the validity of this result for other leguminous plants is not known. Nitrogenous fertilisers often increase the growth of the leguminous crop, but reduce, often considerably, the amount of nitrogen fixed. Thus, soybeans only seem to give high yields in the Middle West of America if they can use nitrate nitrogen from the soil to supplement the nitrogen they fix.[3] But adding nitrates or ammonium salts to the soil will reduce the amount of nitrogen fixed by the crop, though, again for soybeans, additions that cause appreciable

[1] *Antonie van Leeuwenk.*, 1947, **12**, 85.

[2] See, for example, H. E. Hampton and W. A. Albrecht, *Missouri Agric. Expt. Sta., Res. Bull.* 381, 1944.

[3] A. G. Norman and L. O. Krampitz, *Proc. Soil Sci. Soc. Amer.*, 1946, **10**, 191; G. D. Thornton, ibid., 1947, **11**, 249.

increases of growth may not reduce the amount of nitrogen fixed appreciably. For small-seeded legumes, however, such as clovers and lucerne, the initial level of soil nitrates must be adequate to allow the young plant to becomes established; but adequate soil nitrates also appear to be necessary if for any reason carbohydrate assimilation is going on so quickly that its concentration in the plant rises too high compared with the nitrogen supply. Table 72, taken from some work of E. B. Fred and his co-workers,[1] illustrates this point for soybeans growing in nitrogen-poor soil during bright summer weather in Wisconsin. Under these conditions they made poor growth with little nitrogen fixation, but adding calcium nitrate increased both growth and nitrogen fixation markedly, presumably by reducing the carbohydrate-nitrogen ratio in the plant. Further, putting the plant in the shade, by reducing the carbohydrate level, also allowed nitrogen fixation to begin again.

TABLE 72

Effect of Nitrogen Supply and Shade on Nitrogen Fixation by Soybeans at Madison, Wisconsin

5–8 plants per pot. Sown, 1/7/37. Harvested, 30/8/37
Nitrogen added or pots put in shade, 28/7/37

Nitrogen added per pot as $Ca(NO_3)_2$ mgm.	Where pot kept	Dry matter in plants, gm.	Per cent nitrogen in dry matter	Nitrogen fixed, mgm.
0	in sun	4·2	1·14	2·6
5		20·7	1·26	35·6
10		28·5	1·28	43·7
25		30·8	1·45	63·3
50		37·7	1·72	67·7
0	in shade	8·9	2·20	25·6
0	in shade till 9–8–37 then in sun	18·7	1·98	54·7

Leguminous plants can sometimes excrete nitrogenous compounds into the soil, but the rare conditions under which this happens are not yet understood. Thus, Virtanen,[2] in Helsinki, found that peas and red clover would excrete up to 70 per cent of the nitrogen they fix, and this excretion appears mainly as aspartic acid or its degradation product β-alanine. He also found that these plants would take up later in the season some of the nitrogen they excreted earlier on and that the excreted nitrogen could be taken up by grasses or cereals growing along

[1] *Proc. Natl. Acad. Sci. Wash.*, 1938, **24**, 46.
[2] See, for example, his book *Cattle Fodder and Human Nutrition*, Cambridge, 1938.

with the legume. Some pot experiments made by H. G. Thornton and H. Nicol[1] at Rothamsted also indicate that nitrogen excretion may also occur here. Lucerne and Italian rye-grass were grown together in sand, and four months after sowing, at the end of July, the lucerne contained 1,000 mgm. of nitrogen and had apparently transferred 80 mgm. to the rye-grass, whilst after five months it contained 1,300 mgm. and had apparently transferred 250 mgm. to the grass.

Nitrogen excretion by a legume is probably a sign that nitrogen fixation is occurring faster than nitrogen utilisation, the surplus nitrogen being excreted. This circumstance would thus only occur under certain climatic conditions—long days with low maximum temperatures and cool nights probably being one of them[2]—and it was only under these conditions that R. H. Roberts was able to show that grasses actually benefited from an associated legume.[3]

TABLE 73

Yields and Nitrogen Contents of Different Oats-Vetch Mixtures

Weight of seed sown per acre in lb.		Yield of dry matter per acre in lb.			Per cent nitrogen in dry matter		Yield of nitrogen in lb. per acre		
Oats	Vetches	Oats	Vetches	Total	Oats	Vetches	Oats	Vetches	Total
200	—	4800	—	4800	1·14	—	55·0	—	55·0
150	50	4100	1230	5330	1·33	2·70	54·5	33·3	87·8
100	100	3420	2060	5480	1·29	2·72	44·0	56·2	100·2
50	150	2430	2680	5110	1·40	2·86	34·0	76·7	110·7
—	200	—	3200	3200	—	3·06	—	98·0	98·0

It is very difficult to establish if and when nitrogen transfer takes place in the field. Mixed cropping with a non-legume and a legume, or in the actual experiments that have been made of a cereal or grass with a legume, nearly always results in the nitrogen content in the dry matter of the cereal or grass being raised, and that in the legume being lowered. But the yield of the non-legume and the total amount of nitrogen it takes up per acre have nearly always been reduced. This last result may not, however, hold for pastures, but suitable experimental data to test this point do not seem to be available. Table 73, which gives the results of a Rothamsted field experiment[4] on the effect of growing oats and vetches together, is a typical illustration of the few results that have been obtained all over the world with cereals and

[1] *J. Agric. Sci.*, 1934, **24**, 269. See also J. Nowotnowna, ibid., 1937, **27**, 503.
[2] O. Wyss and P. W. Wilson, *Soil Sci.*, 1941, **52**, 15; G. Bond and J. Boyes, *Ann. Bot.*, 1939, **3**, 901. See P. W. Wilson's monograph for a detailed discussion.
[3] *J. Amer. Soc. Agron.*, 1946, **38**, 947.
[4] *Rothamsted Ann. Rep.*, 1932, 148.

forage grasses. The results are consistent with the hypothesis that the vetches are excreting nitrogen which the oats are taking up, but they cannot be interpreted as proving this hypothesis, for the results can equally well be interpreted as showing that the vetches, by fixing their own nitrogen, do not draw on the nitrates present in the soil, consequently the fewer oat plants in the mixed crop have the same amount of soil nitrates to draw on as the pure crop. The cause of the decreasing nitrogen content of the vetch plants with increasing proportion of the oat crop would then be interpreted as being due to a decrease in the efficiency of nitrogen fixation as the vetch suffers increasing competition with the oat crop, and in particular possibly due to the decreasing average intensity of daylight it is growing in as the oat crop becomes heavier. These and some other results to be given in this section will be discussed again in Chapter 28 in connection with the effect of growing two crops together, and of one crop on its successor.

A leguminous crop can, though it need not, enrich the soil in nitrogen. When it does so, the process is probably through nitrogen products being liberated into the soil when the nitrogen-rich nodules slough off the roots. This sloughing-off of nodules takes place frequently in perennial leguminous plants as the nodules are only fairly short-lived structures, and it can be encouraged by cutting the legume; thus mowing or grazing a clover or lucerne ley will cause many of the nodules to slough off.[1]

The amount of nitrogen a leguminous plant adds to the soil depends on many factors. Forage legumes, such as clovers and lucerne, usually add much more nitrogen to the soil than the grain legumes, such as beans, peas or soybeans; and the forage legumes appear to add more to the soil if they are grazed than if mown for hay. No detailed analysis has yet been made of the factors that encourage leguminous crops to add nitrogen to the soil, but a vigorous crop, obtained by ensuring an adequate supply of potash, phosphate and lime, adds more nitrogen to the soil than a half-starved one, though this may only come through the vigorous crop leaving a larger weight of residues behind in the soil. This effect of adequate mineral fertilisers is certainly very marked on the residual value of a leguminous green manure crop, when the whole crop is returned to the soil.

The amount of nitrogen different legumes return to the soil probably depends very strongly on their rooting habits. Little work has been done on these lines, but annual grain legumes, such as peas, seem to have a restricted root system which obtains all its nodules in a short space of time. Perennial legumes, such as clovers and lucerne, have a root system that is growing throughout the season, and which can,

[1] J. K. Wilson, *J. Amer. Soc. Agron.*, 1942, **34**, 460.

therefore, form new nodules for a much longer period of the year, and this is a possible reason for the great difference between the relative amounts of nitrogen these two groups of legumes add to the soil.

No quantitative estimates have been made on the form of nitrogen compounds added to the soil. Some nitrogen compounds are released as old nodules decay, some may be excreted directly into the soil, and some will be present in the living and dead root fibres. Some rough estimates indicate that clovers and lucerne may add about 150 to 200 lb. per acre of nitrogen annually to the soil; they may also add about 1 to 2 tons per acre of root fibre annually (see p. 431), and this could well contain the 150 to 200 lb. of nitrogen estimated to be added to the soil. Hence, the dead root fibres may be the reservoir of the added nitrogen compounds. Few experiments seem to have been made on the proportion of the nitrogen fixed by a leguminous crop that remains in its root system, but some pot experiments of I. E. Miles[1] in Mississippi indicate that the subtropical summer forage legumes—velvet beans, lespedeza and kudzu—retain about 20 to 30 per cent of the nitrogen they fix in their root systems whilst the temperate forage legumes, such as clover and vetch, only retain 10 to 15 per cent and are therefore less efficient legumes for increasing the nitrogen supply in the soil unless they are grazed off or ploughed in.

Leguminous trees also may enrich the soil in nitrogen, and they are used in some Indian and Ceylon tea gardens, both for shade and for supplying the tea bushes with available nitrogen. H. R. Cooper[2] has given illustrations of where they seem to add more than 60 lb. of nitrogen per acre annually to the soil, but the mechanism of this addition could be entirely through the return of the tree leaves to the soil without the need of assuming any appreciable excretion from the roots. G. H. G. Jones[3] has also given an illustration from Kenya where the leguminous bush *Glycine javanica* adds 160 lb. per acre of nitrogen to the soil annually for the first five years of colonising land, but which falls to 100 lb. per acre as the nitrogen content of the soil rises.

The actual amounts of nitrogen fixed by leguminous crops is difficult to estimate accurately, and it is possible that many of the estimates given in the literature may be too high owing to the great difficulty of determining accurately the amount of nitrogen in the soil. Some typical figures are given by T. L. Lyon and J. A. Bizzell[4] at Cornell. They found that two courses of a rotation consisting of one-year clover, cut for hay, and four years' grain crops added 200 to 300 lb. of nitrogen per acre to the soil and 300 to 400 lb. to the harvested crops, compared

[1] *Mississippi Agric. Expt. Sta., Circ.* 126, 1946.
[2] *Indian Tea Assoc., Mem.* 6, 1946. For another example, see *Plant. Chron.*, 1945, **40**, 135.
[3] *E. Afric. Agric. J.*, 1942, **8**, 48.
[4] *J. Amer. Soc. Agron.*, 1933, **25**, 266; 1934, **26**, 651.

with a similar rotation in which timothy grass replaced the clovers, indicating that each clover crop had fixed between 250 and 350 lb. of nitrogen per acre,[1] and this is comparable with the amount of nitrogen other workers have found a good crop of lucerne can fix in a year.[2] Soybeans, field beans (*Vicia faba*) and peas harvested for grain on the other hand, depleted the soil of nitrogen as much as ordinary cereal crops: they fixed between 100 and 200 lb. of nitrogen, but it all appeared in the harvested material. Table 74 gives some of their results for five courses of a two-year rotation of legume-cereal,[3] the cereal being either rye or barley, and it shows that the yield of the following cereal crop largely depends on the amount of nitrogen the legume adds to the soil.

TABLE 74

Amount of Nitrogen Fixed by Leguminous Crops, and their Influence on a following Cereal Crop

Mean of two experiments, each five courses of legume-cereal (rye or barley) rotation

	Nitrogen harvested in		Gain or loss of nitrogen in the soil per rotation lb. per acre	Yield of cereal grain cwt. per acre
	Leguminous crop lb. per acre	Cereal crop lb. per acre		
Lucerne	299	66	122	23·2
Clover	125	51	115	19·4
Sweet clover	170	51	84	18·9
Soybeans	176	29	—8	11·8
Field beans	103	25	—20	10·6
Cereal every year	—	22	—10	8·7

It appears that some leguminous crops, such as soybeans and field beans, can only enrich the soil if they are either ploughed in as green manure or fed off either on the land itself or in stalls and the animal manure returned to the land. On the other hand, L. Yankovitch,[4] in Tunis, apparently found that annual legumes such as peas, beans, vetches and lentils fixed between 400 and 500 lb. of nitrogen per acre and added about 200 lb. per acre of this nitrogen to the soil, and the subsequent crop of millet responded very markedly to this residue.

Leguminous crops must not be assumed always to fix 100 lb. per

[1] E. Bruce Levy (*J. Farmers Club*, No. 6, 1949) states that wild white clover will fix 400 lb. per acre of nitrogen in good New Zealand pastures.

[2] See, for example, R. C. Collison, H. G. Beattie and J. D. Harlan, *New York Agric. Expt. Sta., Tech. Bull.* 212, 1933; E. S. Hopkins and A. Leahey, *Canada Dept. Agric., Publ.* 761, 1944.

[3] T. L. Lyon, *Cornell Agric. Expt. Sta., Bull.* 645, 1936.

[4] *Ann. Serv. Bot. Agron. Tunisie*, 1940, **16**, 303.

acre of nitrogen annually when growing well, though this figure is probably a good minimum figure for an actively growing forage legume such as a clover. Table 73 implies that the vetch crop might have fixed this amount if it took no nitrogen from the soil, and beans in England may fix this amount under the same conditions. On the other hand, A. G. Norman[1] finds that soybeans growing on Iowan prairie soils do not often fix more than 20 to 25 lb. per acre of nitrogen, equivalent to a hundredweight of sulphate of ammonia, and this is removed in the crop. Now that isotopic nitrogen N^{15} is becoming available to research laboratories, it may be possible to estimate more accurately the quantity of nitrogen arable leguminous crops actually fix in the field.

[1] *Proc. Soil Sci. Soc. Amer.*, 1947, **11**, 9.

CHAPTER XVII

THE TEMPERATURE OF THE SOIL

The soil derives its heat almost entirely from the sun, the small amounts due to oxidation of organic matter and to radioactivity being, so far as is known, negligible in influencing plant growth. The temperature of the soil depends, therefore, on the amount of heat received by the surface and the way in which this heat is dissipated.

The quantity of radiant energy reaching the soil depends on the position of the sun, the opacity of the atmosphere, the aspect of the land and the vegetation cover. The atmosphere absorbs nearly all the short-wave ultra-violet radiation, but if the air is clear and dry and the sun is overhead, it transmits most of the visible and heat rays. Water vapour, however, absorbs much of the long-wave radiation, particularly that with a wavelength around 10 μ, and water droplets scatter and absorb much of the general radiation; and even if the sky appears to be clear, these absorptions can be very noticeable when the sun is low in the sky. Hence, more of the incoming radiant energy reaches the surface of the earth in arid climates than in humid; and more when the sun is high in the sky, as in the equatorial regions, than when low, as in the polar. The effect of topography is simply due to the fact that a surface at right angles to the sun's rays receives more energy than an equal area sloping in any other direction. Hence, in the Northern Hemisphere a south slope is warmer than a north slope, and is sufficiently so to produce marked vegetation differences.

The effect of cloud on the incoming energy reaching the earth's surface at Rothamsted can be seen in Fig. 25.[1] The maximum amount of energy that could be received per day increases from about 100 calories per sq. cm. in mid-December to 700 in mid-June, whilst the actual mean daily values increase from about 40 to 400 calories during this period. Table 75 gives the mean daily and monthly figures for the ten years 1931–40, and shows that at Rothamsted about 64,000 calories are received per sq. cm. for the seven months of the growing season, from March to September, and about 76,000 calories for the year.[2] If all this energy were used to evaporate water from the land surface, about 50 inches of water per year would be evaporated.

[1] W. B. Haines, *Quart. J. Roy. Met. Soc.*, 1925, **51**, 95–100.

[2] Using the acre instead of the square centimetre as the unit of area, this is equivalent to $3\frac{1}{2}$ million units of electricity (kilowatt hours), to $4\frac{1}{2}$ million horse-power hours, or to the heat developed by burning some 400 tons of coal. Only about 0·5 per cent of this is recovered in the crop.

This figure can be compared with the actual evaporation of about 18 inches per year by an actively growing crop and of about 14 inches per year from a bare soil, given in Table 87, on page 370.

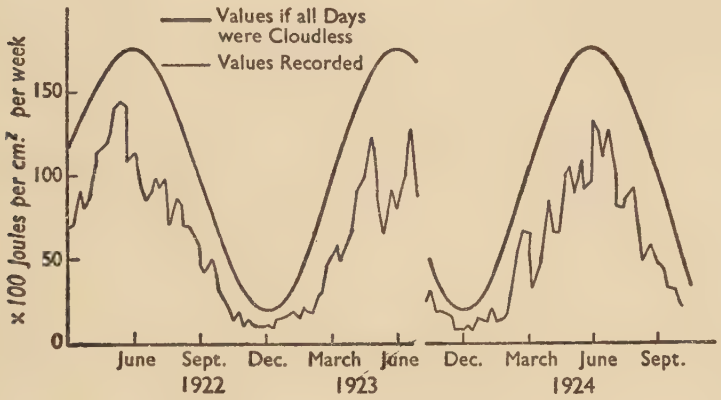


FIG. 25. Solar radiation received at Rothamsted.

TABLE 75

Mean Value of the Daily and Monthly Radiation at Rothamsted

Period: 1931-40

Months	Cals. per cm.² per day	Cals. per cm.² per month	
January	54·2	1680	
February	97·6	2733	
March	202·5	6277	
			10690
April	260·8	7824	
May	353·2	10949	
June	405·2	12156	
			30929
July	361·3	11200	
August	306·0	9486	
September	227·7	6831	
			27517
October	129·4	4011	
November	63·6	1908	
December	39·9	1237	
			7156
Total for year			76292

The Heat Balance of a Soil

Of the radiation falling on a soil or crop, part is absorbed and the rest is reflected back. A bare wet soil reflects back about 7 to 10 per cent of the incident energy on a sunny day, a bare dry soil about double, and a crop about three times this figure.[1] The absorbed energy is converted into heat and is dissipated in three ways: part evaporates water, part heats the soil and air, and part is re-radiated.

The temperature of the surface layer of bare dry soil on a clear sunny day rises rapidly from sunrise until noon, and then falls to sunset,

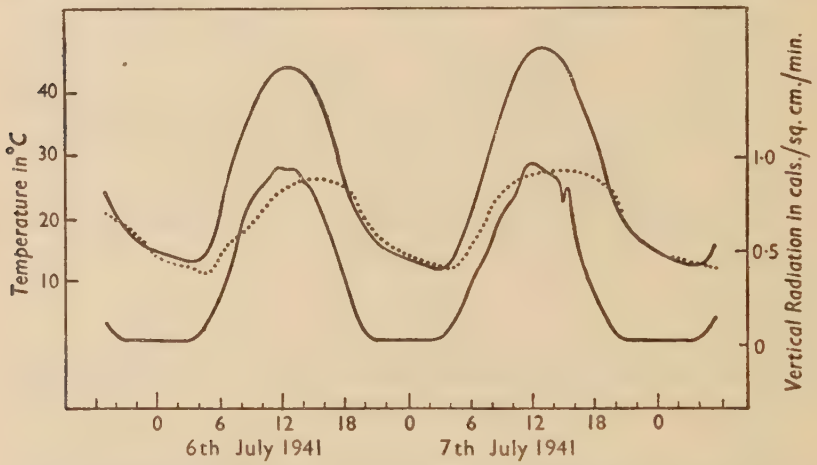


Fig. 26. Relation between incoming solar radiation and the air and soil surface temperatures on two cloud-free days at Rothamsted.
Upper Full Curve: The temperature of the surface of the soil.
Lower Full Curve: The solar radiation received by the soil surface.
Middle Dotted Curve: The air temperature 4 ft. above the ground (in the screen).

following very closely the rate of absorption of incident radiation; after sunset it continues to lose heat at a slower rate until sunrise, as is shown in Fig. 26.[2] This is because the soil is re-radiating heat to the sky. If the atmosphere absorbed none of the re-radiated heat, the rate of loss of heat from the soil would be proportional to the fourth power of its absolute temperature, and since this is about 280° to 300° K., the wavelength band at which the maximum amount of energy is being re-radiated is around 10 μ. Now this is just the wavelength band that water vapour molecules absorb strongly, and having absorbed energy at this wavelength, they then re-radiate it at the same wavelength, but in all directions equally. Thus, at a given level in the atmosphere,

[1] A. Angstrom, *Geograf. Ann.*, 1925, p. 323.
[2] H. L. Penman, *Quart. J. Roy. Met. Soc.*, 1943, **69**, 1.

the water vapour there effectively reflects half the outgoing radiation in this wavelength band back towards the earth, and if there is a thick belt of moist air very little of the radiation of this wavelength that leaves the earth's surface will penetrate into space. No exact calculations can yet be made of the effect of cloud and water vapour in the atmosphere on this loss, but D. Brunt[1] has shown that to a useful approximation it is reduced by a factor

$$(0{\cdot}56 - 0{\cdot}092\sqrt{e})\,(1 - 0{\cdot}09m),$$

where e is the water vapour pressure in millimetres of mercury in the air 6 feet above the soil and $m/10$ is the fraction of the sky covered with cloud. Thus, desert regions are characterised by great inflows of radiant energy during the day and great outflows during the night, with the consequence that the daily variation of surface soil temperature is very great. The conditions differ in the humid regions, because they can still receive large amounts of radiant energy during the day, for this radiation comes from the sun, which has an effective radiation surface temperature of 6,000° K., so that the wavelength band at which the maximum amount of energy is being radiated is about 0·5 μ. But the soil surface cannot lose much energy during the night because of the blanketing effect of the water vapour in the atmosphere. At Rothamsted in clear summer weather this daily fluctuation is about 35° C. when the surface soil is dry, and it exceeds 50° C. in subtropical deserts. If the soil is wet, about half the absorbed energy is used for evaporating water, so that although the shape of the diurnal surface temperature curve is unaltered, the daily variation at Rothamsted is reduced from about 35° C. to about 20° C.

It is possible to control the surface temperature of a soil somewhat by altering its colour, so altering the proportion of the incoming radiation that is reflected. Whitening the surface, for example, by spreading a thin film of chalk on it, increases, and blackening it,[2] as, for example, with soot, decreases the amount of energy reflected; and hence the soil should be cooled by the one and warmed by the other. Other methods of increasing the soil temperature, which is often very desirable in the temperate regions, are to improve the drainage of the soil, so decreasing the amount of water that has to be evaporated before the air content of the surface soil becomes appreciable.

The Influence of Vegetation on Soil Temperatures

The fundamental effect of a crop, or of crop residues, on the surface

[1] *Physical and Dynamical Meteorology*, 2nd ed., Cambridge, 1939.

[2] E. Wollny, *Forsch. Geb. Agrik. Phys.*, 1878, **1**, 43; 1881, **4**, 327; R. K. Dravid, *Indian J. Agric. Sci.*, 1940, **10**, 352. See *Indian Farm.*, 1941, **2**, 47, for a Canadian experiment on increasing the yield of cantaloupe melons by the use of black paper.

temperature of a soil is to reduce both the diurnal and the seasonal fluctuations. This is because during the daytime most of the incident radiation is absorbed by the vegetation above the soil level, so that the main supply of energy to the soil is the long-wave radiation of the plant leaves, for the air that is heated by the absorbing leaves transports very little of this heat to the soil. Correspondingly, at night the soil cannot radiate energy into space, for it is absorbed and radiated back by the vegetation. The main region of energy loss by radiation is the plant leaves and, in so far as the air cannot supply energy by condensing water vapour as dew, it becomes cooled, and so sinks to the soil level; but air because of its low heat capacity is a poor transporter of heat from the soil to the leaves, so again the heat lost from the soil surface is low. Thus, in clear weather the air temperature over a crop is higher than the soil surface temperature during the day, but lower during the night; whilst the air temperature over a bare soil is lower than the soil surface temperature during the day, but higher during the night.

One aspect of the control of air temperature by vegetation, of great importance to fruit growers, is the production of cold air during clear spring nights. When radiation takes place from vegetation, such as long grass, for example, the heat is lost from the grass leaves which cool the air in contact with them. This air becomes heavier as it cools and, if the grass is thick, it will be entrapped between their blades and form a stationary layer which, since it has a low heat conductivity, will transport little heat from the soil surface to the cooling blades of grass. The air temperature just above the grass will, therefore, cool very rapidly, and if it is fairly dry, it will have to be cooled below the freezing-point before water vapour begins to condense out and to supply heat to the grass for radiation. If, however, the vegetation is fairly thin, small convective air currents between the radiating leaves and the soil surface will be present, so that heat can be transferred from the soil to the radiating surfaces, and the fall of air temperature above the vegetation will be correspondingly reduced. Thus, C. E. Cornford[1] found that the minimum air temperatures 3 feet above the ground on some flat land in Kent, after a clear, still night at the end of May, were: above bare soil, 49·5°F.; in a wood, 49°F.;[2] in a short-grass meadow, 45·7°F.; and over a longer grass meadow, 43°F.

Surface mulches, such as layers of straw, have the same effect as a cover crop of preventing the exchange of heat between the soil surface

[1] *Quart. J. Roy. Met. Soc.*, 1938, **64**, 553.

[2] The reason for the small fall in the wood is that the radiation takes place at tree-top or canopy level and the cold air formed there sinks and mixes with the large volume of air in the wood itself, thus only causing a small drop in temperature.

and the air. Thus, W. S. Rogers[1] found in some Kent strawberry beds that there could be a 13·5°F. temperature difference on either side of a straw mulch on a clear spring night, and the minimum air temperature might be 7°F. lower over a straw mulch than a bare soil.

This blanketing effect of vegetation or mulches may have an important effect on the vegetation in winter, for it reduces the penetration of frost into the soil. Thus, E. J. Salisbury[2] quotes an example where frost penetrated a sandy loam to a depth of 5·5 to 8·5 cm. if bare, to a depth of 2·5 to 3·5 cm. under rough grass, to less than 2 cm. under some bushes, to 1·5 cm. in open hazel copse, where there was no litter,

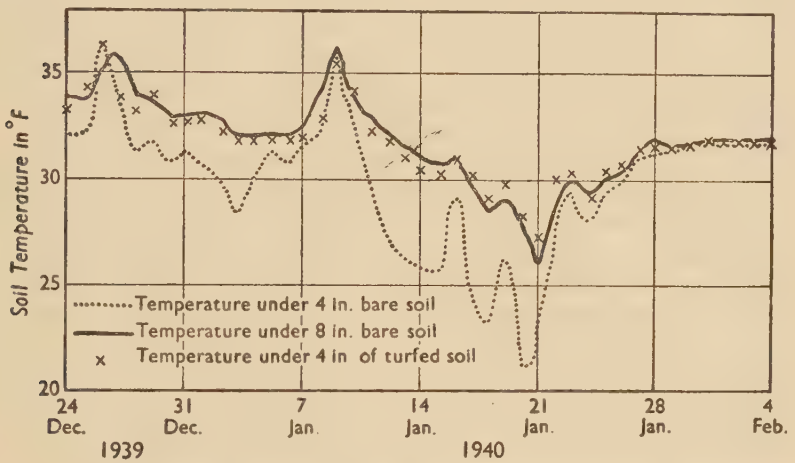


FIG. 27. The effect of a turf covering on the sub-surface temperature of the Rothamsted soil during a hard frost.

and did not enter at all where there was litter. R. K. Schofield[3] found at Rothamsted and Woburn that a grass cover was even more effective, being equivalent to 4 inches, or 10 cm., of soil, as is shown in Fig. 27; that is, if frost penetrated 8 inches in bare soil it only penetrated 4 inches under short grass. F. A. Post and F. R. Dreibelbis,[4] in Ohio, have given another example; they found that soil became frozen to a depth of 2 inches or more many times during the winter when under wheat, only a few times under grass, and not at all under forests.

Snow also protects the soil against penetration of frost, with the consequence that the soil may be warmer and frozen to a less depth in an extremely cold winter if there is much snow than in a not so cold winter without snow.

Vegetation and mulches thus reduce the fluctuations in the temperature of the surface soil, and the thicker the vegetation the smaller

[1] *Imp. Bur. Hort., Tech. Comm.* 15, 1945.
[2] *Quart. J. Roy. Met. Soc.*, 1939, **65**, 337.
[3] *Quart. J. Roy. Met. Soc.*, 1940, **66**, 167.
[4] *Proc. Soil Sci. Soc. Amer.*, 1942, **7**, 95.

the temperature fluctuations in the soil. Forests, by ensuring that the absorbers and emitters of radiant heat, i.e. their leaves, are high above the soil, give a deep column of fairly still air in which convection can readily take place and which, therefore, acts as a buffer between absorption and emission of radiation. The plants in a grass pasture, on the other hand, merely remove the emitters and absorbers of radiation a small distance from the soil, and hence give a small depth of stagnant air above the surface.

This power of vegetation to reduce fluctuations of the soil surface temperature, and particularly to lower its maximum day temperature, is used in practice in the tropics to protect shallow-rooting crops, such as cacao and coffee, against the high temperatures that occur during the dry season by interplanting these crops with deep-rooting tall shade trees. The daily fluctuation in the temperature of the surface few inches of a soil under forest is often only one-third that of a bare soil.

Vegetation affects the seasonal changes in the soil surface temperature. Soil under vegetation warms up slower in the spring and cools down slower in the autumn than bare soil. But little is known about the magnitude of this effect or how it varies from year to year. At Rothamsted, at a 4-inch depth below the surface, bare soil is always cooler than turf, except in June and July, and the difference between these two is largest in autumn. On a ten-year average (1930–9) soil under turf is 2°F. warmer in October and November than bare, but is only 1°F. warmer during the winter and spring, whilst from May to August it is within 0·5°F. of the bare soil temperature.

The Variation of Soil Temperature with Depth

The daily fluctuation of temperature in the surface soil causes a daily temperature wave to penetrate into the soil. This wave is heavily damped, as is shown in Fig. 28 for a number of cloudless summer days at Rothamsted, and becomes very small below 12 inches; and as it penetrates, the time the maximum value is reached becomes later in the day. The thermal conductivity of the soil controls the rate of damping—the lower the conductivity the smaller the diurnal variation at a given depth. Thermal conductivity is very dependent on soil tilth,[1] for soil particles and water have about a hundred and about twenty-five times the thermal conductivity of still air respectively, so that the smaller the area of contact between soil crumbs the lower the thermal conductivity. For the undisturbed subsurface soil it is only slightly dependent on moisture content, rising a little as the soil becomes wet, though this dependence will probably be more marked on coarse

[1] W. O. Smith and H. G. Byers, *Proc. Soil Sci. Soc. Amer.*, 1938, **3**, 13.

than fine-textured soils. Thermal conductivity depends also to some extent on the texture of the soil, being rather higher for sandy soils than for clay soils. Thus, R. K. Schofield[1] found that the sandy Woburn soil cools down quicker in frosty weather than the heavier Rothamsted soil. It also warms up quicker in the spring, thus it is on the average 1° F. warmer at 4 inches and 1·5° F. at 8 inches during the spring months, whilst during the autumn the mean soil temperatures are the same.

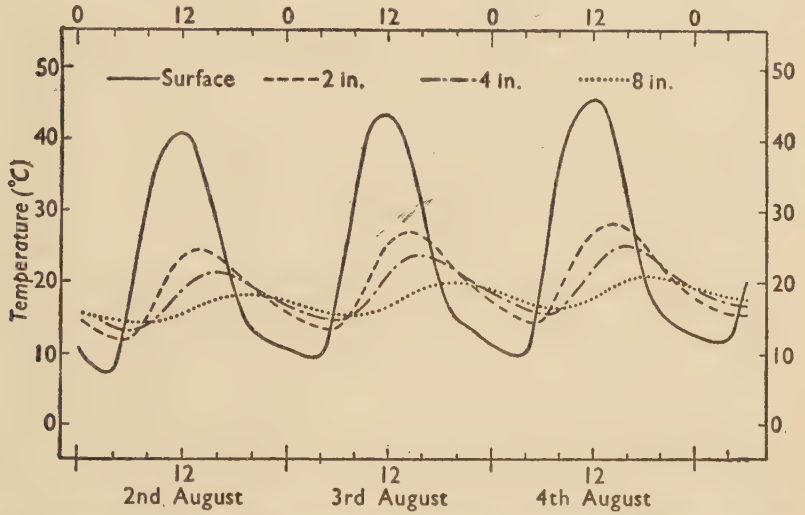


Fig. 28. The damping of the daily temperature wave with depth in a bare Rothamsted soil.

The temperature of some soils in the spring can be increased by improving their drainage, but it is not quite clear how far this is due to an increase in their air content—thus decreasing their heat conductivity—or to a decrease in their water content—thus decreasing their specific heat—and how far to increasing their maximum daily surface temperature through a smaller proportion of the incoming radiation being used for evaporating water, so leaving a larger proportion for warming the soil.

The seasonal variation of temperature at a given depth is complex, for during the summer heat is moving from the surface downwards and there is a regular downward temperature gradient; during winter heat is moving upwards and there is then a regular upward gradient; whilst in the spring, heat is moving downwards from the surface and upwards from below, and during the autumn there is a zone above which it is moving upwards and below which it is moving downwards.

[1] *Quart. J. Roy. Met. Soc.*, 1940, **66**, 167.

But the range of temperature variations naturally decreases at increasing depth, and the mean annual temperature in the root zone is probably independent of depth.

The actual net changes in the amount of heat held by the soil are only small. Thus, H. L. Penman estimates that at Rothamsted the heat content of the top 4 feet of soil rarely changes by as much as 30 calories per day, or probably by 800 calories during the year. These correspond to the heat required to evaporate a layer of water 0·5 mm. and 14 mm. deep respectively.

CHAPTER XVIII

THE SOIL ATMOSPHERE

THE SOIL PORES that are not filled with water contain gases, and these gases constitute the soil atmosphere. But its composition differs from that of the free atmosphere because the plant roots and organisms living in the soil remove oxygen from it and respire carbon dioxide into it. Thus, it is richer in carbon dioxide and poorer in oxygen than the free atmosphere.

Most crops can only make vigorous growth if the carbon dioxide concentration around their roots is not too high, nor the oxygen concentration too low (see p. 423). Hence, the rate of transfer of carbon dioxide from the root zone to the atmosphere and of oxygen from the atmosphere to the root zone is a soil property of fundamental importance to the crop, and in humid soils the rate of oxygen penetration probably limits root growth more often than the rate of carbon dioxide removal: the oxygen supply is as important in humid soils as is the water supply in arid.

The principal paths along which the carbon dioxide and the oxygen move in the soil are those pores containing the soil atmosphere that form a continuous system throughout the depth of a well drained soil. Good aeration can only occur in well drained soils which have an adequate proportion of their volume occupied by such pores, and several workers have shown that this proportion should be at least 10 per cent.[1] There are, however, some soils, such as the Rothamsted clay loam,[2] which when wet but well drained appear to have very little air in the continuous pores, but on which plants do not seem to suffer from bad aeration. The reason for this difference in behaviour from other clay soils is not known, but presumably must be due in part at least to their subsurface soil being filled with cracks down which oxygenated rain-water can percolate fairly quickly in the deeper subsoil. Aeration problems thus fundamentally arise either in soils with a high water table or in heavy soils when wet; they do not arise in well drained sandy soils or in heavy soils that have been partially dried out by the plant roots.

[1] J. Kopecky, *Int. Mitteil. Bodenk.*, 1914, **4**, 138 (for cereals); L. D. Baver and R. B. Farnsworth, *Proc. Soil Sci. Soc. Amer.*, 1941, **5**, 45 (sugar-beet on a heavy soil in Ohio); R. E. Stephenson and C. E. Schuster, *Soil Sci.*, 1937, **44**, 23 (walnuts on a heavy soil in Oregon).

[2] For another example, see A. Woodburn, *Agric. Engng.*, 1945, **26**, 193, who showed cotton would grow satisfactorily in pots filled with a heavy black Houston clay having no air content when wet but well drained.

The proportion of the total volume of a soil occupied by air is difficult to determine in many soils. One method, which is only applicable to stone-free soils that are coherent and not too compacted, is to push a hollow metal cylinder or box into the soil in such a way that the sampling tool neither loosens nor compresses the soil inside it; the air content is then determined either directly,[1] or by the difference between the volume of the sampling tool and the volume of soil plus water in the sample. This method fails with loose sands or stony soils; the air space in the former, and in the latter if it is open, can, however, be determined fairly readily by impregnating the soil with a hot molten wax,[2] for example, paraffin wax, whilst there are no really satisfactory methods for stony loams or clays.[3]

The volume of air in a well drained soil at field capacity (see p. 355) decreases as the soil becomes heavier, that is, as the silt and clay content increase, but there is no simple relation between it and the mechanical analysis of the soil. It also increases as the soil dries. For sandy soils and light loams in the field, the increase of air content is approximately equal to the amount of water removed from the soil, for every cubic centimetre of water transpired is replaced by one cubic centimetre of air, and this replacement takes place in the same small volumes. But in clay soils the increase in air content is less than the decrease in the volume of water held, and much of the new air space does not occupy the actual pores from which the water was removed. For clays shrink on drying and this shrinkage causes a general subsidence of the soil surface relative to a fixed plane in the moist subsoil, which for English clays may be 2–3 inches in a dry summer.[4] But the shrinkage is not uniform throughout the soil mass; it takes place round many centres, and the more centres around which the contraction takes place, the greater will be the number of cracks that will open, so the better distributed will be this new air space and in consequence the better will be the aeration in the subsoil due to its being dried.

The composition of the soil air is determined by the difference between the rate of production of carbon dioxide in the soil by the plant roots and micro-organisms and the rate of its removal from this zone either into the deeper subsoil or into the atmosphere. The rate of production under natural conditions is not too well established, but a selection of figures is given in Table 76, which shows that up to 10 to 12 grams, or 5 to 10 litres of carbon dioxide can be produced per square metre per day, and a corresponding volume of oxygen is then

[1] As, for example, by W. C. Visser's method (*Soil Sci.*, 1937, **44**, 467).
[2] As, for example, by N. F. Mishchenko's method (*Soil Res.*, 1932, **3**, 24).
[3] For a discussion of the best available methods, see E. W. Russell and W. Balcerek. *J. Agric. Sci.*, 1944, **34**, 123.
[4] W. H. Ward, *Proc. Conf. Biology and Civil Engng.*, London, 1949, 181.

needed.[1] Romell points out that if carbon dioxide is being produced at 7 litres per square metre per day throughout the top 20 cm. of soil, and if gas exchange were prevented, the CO_2 content of the soil in an average soil would double in one and a half hours and would increase tenfold in fourteen.

TABLE 76

CO_2 Evolution and Oxygen Absorption in Natural Field Soils

	CO_2 evolved per sq. metre per day Grams	Oxygen absorbed per sq. metre per day at 15°C. Litres
Broadbalk, dunged plot	4·2[2]	2
J. Stoklasa and A. Ernest[3] (Wheat field)	7·5	4
L. G. Romell[4] (August)	13–20	7–10·5
H. Lundegårdh[5] (August)	2·6–50	1·4–26
P. Hasse and F. Kirchmeyer[6]		
Bare ground	1·6–4·8	—
Rye	5·4–10·2	—
Potatoes	11·8–12·7	—
Lucerne	9·0–21[7]	—
H. Humfield[8]		
Bare ground	1·8	—
Cropped	2–4·4	—

The carbon dioxide produced in the soil can find its way into the atmosphere by a variety of means. In the first place, since the concentration of carbon dioxide is higher in the soil than in the atmosphere, some of it will diffuse into the atmosphere at a rate calculable from the well established theory of the diffusion of gases. Besides this process, changes in soil temperature and in the barometric pressure of the atmosphere will cause the soil atmosphere to expand and contract, and will, in fact, make the soil "breathe", in an amount dependent on

[1] This figure can be compared with the absorption of 10 c.c. of nitrogen per sq. m. per day needed by a lucerne crop fixing 1 cwt. of nitrogen per acre in three months.

[2] Annual evolution divided by 365. Stoklasa and Ernest assume only 200 "active" days, at which rate this value becomes 7·7, closely agreeing with theirs. But at Rothamsted there are more than 200 active days.

[3] *Zbl. Bakt.* II, 1905, **14**, 723. Their total evolution is 13·5, but of this 6 is assumed to come from the roots of the wheat, leaving 7·5 to come from the soil.

[4] *Medd. Skogsförsöksanst.*, 1922, **19**, 125. Forest soils, tree roots included. Summer values only.

[5] *Klima und Boden in ihrer Wirkung auf des Pflanzenleben*, Jena, 1925. English translation from 2nd German ed., *Environment and Plant Development*, by E. Ashby, London, 1931. See also *Soil Sci.*, 1927, **23**, 417.

[6] *Ztschr. Pflanz. Düng.*, 1927, A **10**, 257–98.

[7] It was estimated that 80 per cent of this was due to root respiration.

[8] *Soil Sci.*, 1930, **30**, 1 (Sept. values).

the change of pressure or temperature. Rain also, by bringing dissolved oxygen into the soil (Table 77), will first of all carry oxygen into the upper subsoil and then carbon dioxide into the deeper as it percolates down to the water table.

TABLE 77

Dissolved Oxygen Brought Down in Rain[1]

	Average rainfall (inches) at Rothamsted (28 years)	Dissolved oxygen	
		Parts per million	Lb. per acre
Summer	13·32	9·0	27·12
Winter	15·50	11·2	39·27
Year	28·82	—	66·39

The relative importance of these various processes is still under discussion,[2] but L. G. Romell,[3] in a classical paper published in 1922, showed that the process of diffusion appears to be adequate to effect the exchange at the rates observed. Now the rate of diffusion of carbon dioxide from the soil to the atmosphere is proportional to the CO_2 concentration gradient, and is dependent on the volume of the soil atmosphere. G. Buckingham[4] showed that, to a first approximation, it was solely dependent on this volume and not on the size of the empty pores making up this volume. He considered the rate of diffusion was proportional to the square of the air space in the soil, though H. L. Penman[5] has recently shown that, in the range of air spaces usually met with in agricultural soils, a linear relation between the rate of diffusion and the air space fits the experimental data better than the quadratic, and that Buckingham's formula under-estimates the diffusion rates in this range. This result means that good aeration is directly dependent on the magnitude of the air space: any soil treatment that increases the air space, such as ploughing, cultivating or subsoiling, provided the increase lasts for a period of time, reduces the carbon dioxide content and increases the oxygen content of the soil. Conversely, any operation that reduces the air space, such as rolling the soil, increases the carbon dioxide content, and hence often lowers the *p*H of the soil (see p. 101)—an effect that may be of importance in calcareous loam and sandy soils, and may explain the experience of

[1] E. H. Richards, *J. Agric. Sci.*, 1917, **8**, 331.

[2] See B. A. Keen, *Physical Properties of the Soil*, London (1931), for a quantitative discussion of the relative importance of these processes.

[3] *Medd. Skogsförsöksanst.*, 1922, **19**, 125.

[4] *U.S. Dept. Agric., Bur. Soils, Bull.* 25, 1904.

[5] *J. Agric. Sci.*, 1940, **30**, 437, 570.

farmers that heavy rolling and good consolidation are so essential on them.

The composition of the soil air depends on the relative rates of two opposing processes: the rate of production of carbon dioxide in the soil and its rate of removal from the soil. This rate of removal is continuously fluctuating with every change in structure, moisture content and temperature of the soil, whilst the rate of production is probably much less sensitive to these ephemeral changes; with the consequence that both the CO_2 and the oxygen concentrations in the soil air are continuously fluctuating, and their fluctuations do not necessarily follow each other closely. Fig. 29[1] shows these fluctuations

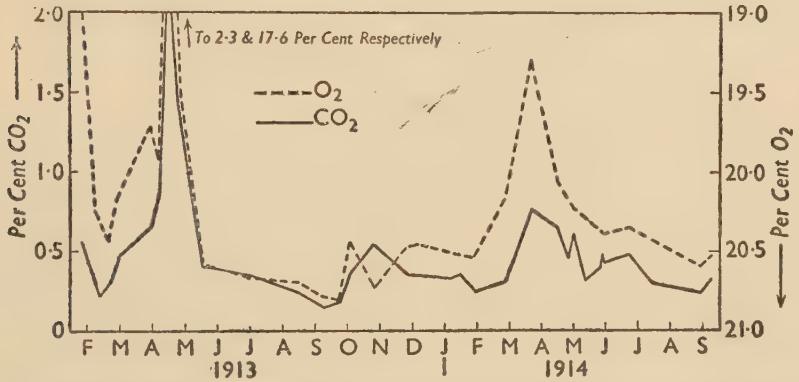


Fig. 29. The oxygen and carbon dioxide content of the soil air in the dunged plot of Broadbalk under wheat.

in the air drawn from a 6-inch depth out of the dunged wheat plot on Broadbalk over a period of twenty-one months. It can be seen that while, on the whole, the carbon dioxide concentration follows the inverse of the oxygen concentration fairly accurately, yet there are occasions when both increase or decrease together (i.e. they have opposite slopes in the figure). But the figure also shows that when diffusion is restricted by the soil being very wet, as in early May 1913 and early April 1914, the oxygen content falls by much more than the carbon dioxide rises. This result, which appears to be generally true,[2] is probably due, as will be explained on p. 343, to much of the carbon dioxide being dissolved in the soil water whilst little of the oxygen is; it is unlikely to be due to the plant roots or soil micro-organisms respiring less carbon dioxide than could be produced from the amount of oxygen they consume.

[1] E. J. Russell and A. Appleyard, *J. Agric. Sci.*, 1915, **7**, 1.

[2] This is shown both in the New York apple orchard results in Fig. 30 and the cacao soils in Table 79.

The composition of the air in the surface layers of arable soil does not usually differ widely from that of the atmosphere when the main fluctuations in composition are smoothed out. The oxygen content is usually over 20·3 per cent, the nitrogen about 79 per cent, and the carbon dioxide between 0·15 and 0·65 per cent, compared with 20·96, 79·01 and 0·03 per cent respectively in the atmosphere. Table 78 gives some typical figures for the composition of the air in the surface soils of north-western Europe.

TABLE 78

Composition of the Air in Soils, per cent by Volume

Soil	Usual composition		Extreme limits observed		Analyst
	Oxygen	Carbon dioxide	Oxygen	Carbon dioxide	
Arable, no dung for 12 months	19–20	0·9	—	—	J. B. Boussingault and Lévy[1]
Pasture land	18–20	0·5–1·5	10–20	0·5–11·5	Th. Schloesing *fils*[2]
Arable, uncropped, no manure:					E. Lau,[3] mean of determinations made frequently during a period of 12 months. Values at depths of 15 cm., 30 cm. and 60 cm., not widely different. (30 cm. values given here.)
sandy soil	20·6	0·16	20·4–20·8	0·05–0·30	
loam soil	20·6	0·23	20·0–20·9	0·07–0·55	
moor soil	20·0	0·65	19·2–20·5	0·28–1·40	
Sandy soil:					
dunged and cropped potatoes, 15 cm.	20·3	0·61	19·8–21·0	0·09–0·94	
serradella, 15 cm.	20·7	0·18	20·4–20·9	0·12–0·38	
Arable land, fallow	20·7	0·1	20·4–21·1	0·02–0·38	
unmanured	20·4	0·2	18·0–22·3	0·01–1·4	E. J. Russell and A Appleyard[4]
dunged	20·3	0·4	15·7–21·2	0·03–3·2	
Grassland	18·4	1·6	16·7–20·5	0·3–3·3	

Under tropical conditions the CO_2 content of the soil air may rise much higher, and the oxygen content fall lower, than these figures during the warm rainy seasons,[5] presumably because of the very rapid evolution of carbon dioxide by the soil organisms on the one hand, and the heavily restricted air space in the soil on the other.

The carbon dioxide content of the soil air usually increases, and the oxygen content decreases, with depth; and this can be very marked during wet periods in heavy or badly drained soils. Fig. 30[6] shows this variation for a well drained sandy soil and a badly drained heavy soil in the apple orchards of Cornell, and Table 79[7] shows it for a

[1] *Ann. Chim. Phys.*, 1853, **37**, 5.
[2] *C.R.*, 1889, **109**, 618, 673.
[3] *Inaug. Diss.*, Rostock, 1906.
[4] *J. Agric. Sci.*, 1915, **7**, 1.
[5] For some results at Pusa, see J. W. Leather, *India Dept. Agric. Mem. Ser.*, 1915, **4**, 85.
[6] D. Boynton and O. C. Compton, *Soil Sci.*, 1944, **57**, 107.
[7] H. Vine, H. A. Thompson and F. Hardy, *Trop. Agric. Trin.*, 1942, **19**, 175, 215; 1943, **20**, 13.

cacao soil in north-west Trinidad during the rainy and the dry seasons. These show that the carbon dioxide content can rise to very dangerous heights in a subsoil where the crop roots ought to be active. Hardy

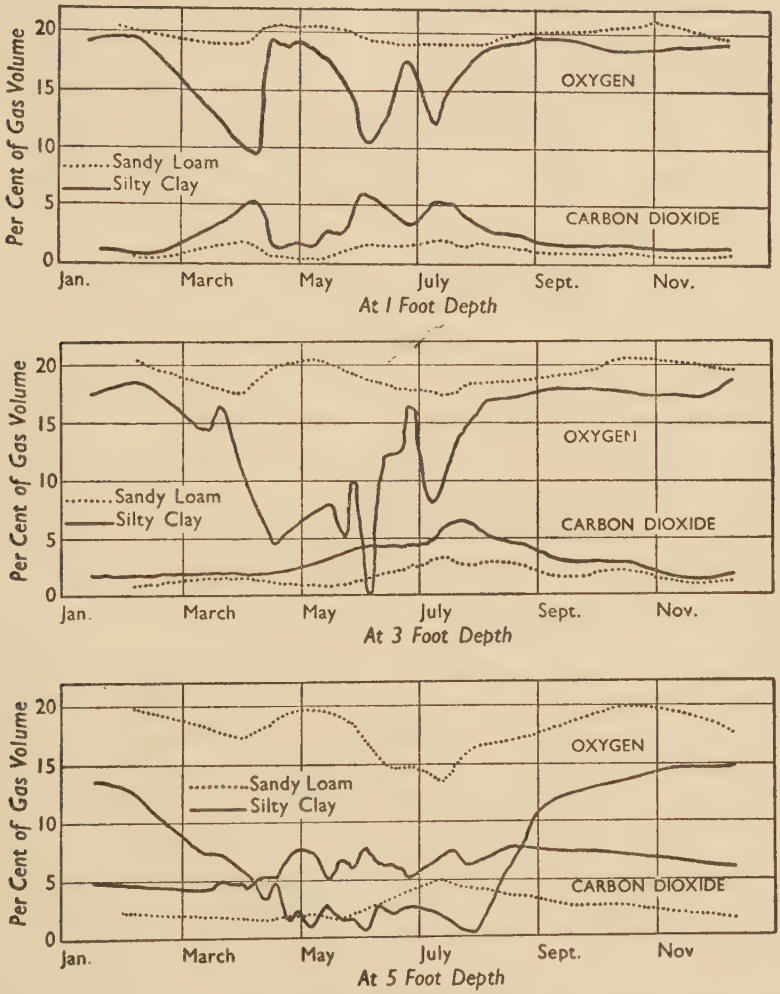


FIG. 30. The oxygen and carbon dioxide contents of the soil air at three depths in a sandy loam and a silty clay apple orchard (Cornell).

also showed, in more detail than is given in Table 79, that the CO_2 gradient was nearly constant down the profile during the dry season, but was much higher in the surface than subsurface layers during the wet.

TABLE 79

The Oxygen and Carbon Dioxide Content of Soil Air under Cacao (Rivers Estate, Trinidad)

Depth of sampling in cm.	Oxygen content		Carbon dioxide content			Carbon dioxide gradient per cent per cm.	
	Wet Oct.–Jan.	Dry Feb.–May	Wet Oct.–Jan.	Early dry Feb.	Late dry April–May	Wet Oct.–Jan.	Dry April–May
10	13·7	20·6	6·5	1·0	0·5	0·65	0·05
25	12·7	19·8	8·5	2·1	1·2	0·13	0·06
45	12·2	18·8	9·7	4·3	2·1	0·04	0·07
90	7·6	17·3	10·0	6·7	3·7	0·01	0·06
120	7·8	16·4	9·6	8·5	5·1	—0·01	0·06
Observed CO_2 diffusion rate from the soil in litres per sq. m. per day . .			6·8	7·5	17·7		

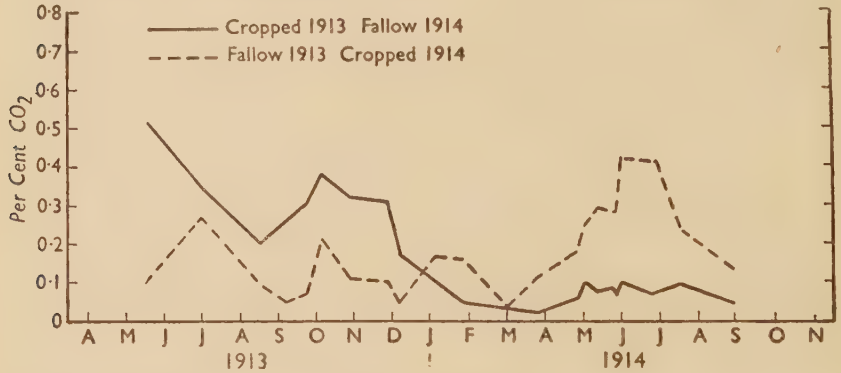


Fig. 31. The effect of a wheat crop on the carbon dioxide content of the soil air (Rothamsted, Hoosfield, wheat and fallow).

The carbon dioxide content of the soil air is higher in cropped than in fallow land (Fig. 31), and this effect is most noticeable when the crop is growing actively. The effect of the type of crop on the composition of the soil air is not well established, as the short period fluctuations in composition and changes in the tilth of the surface soil consequent upon growing the crops usually swamp any differences between them. There is, however, as shown in Table 78, little doubt that the air in soils carrying lucerne or permanent pastures is richer in carbon dioxide than that in arable soils.

The effect of dressings of farmyard manure on the carbon dioxide content of the soil air is less than one might expect, presumably because although the rate of carbon dioxide is increased, the air space in the soil, and hence the rate of diffusion of the carbon dioxide into the atmosphere, is also increased. Fig. 32 shows the carbon dioxide contents of two neighbouring plots on Broadbalk, one of which has been unmanured since 1843, and the other which has received 14 tons of farmyard manure practically every year since then. The main difference between them lies in the carbon dioxide contents when the soil is wet

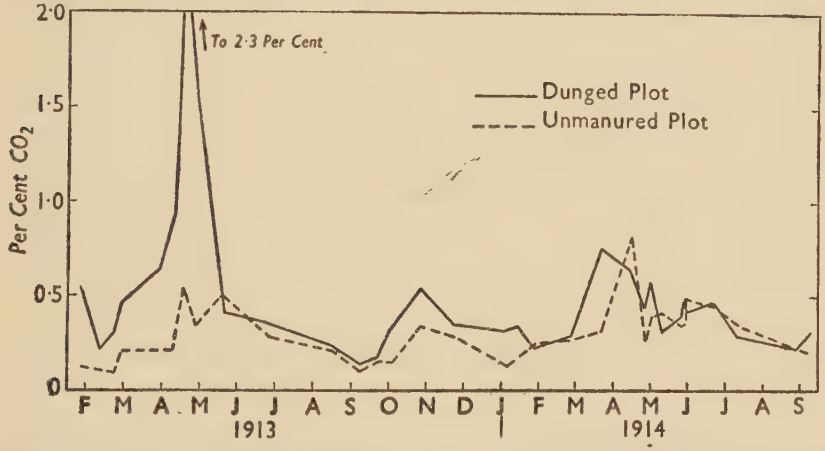


Fig. 32. The effect of annual dressings of farmyard manure on the carbon dioxide content of the soil air (Broadbalk, wheat).

and diffusion slowed down. The soil was wet throughout the period April–May 1913, whereas it was dry throughout this period in 1914, and this is the probable cause of the much greater difference between the carbon dioxide contents of the two plots in the former spring.

Green manuring, particularly if the crop is fairly succulent, will also put up the carbon dioxide content of the soil air. This may have two consequences. If seeds are sown too soon afterwards, the carbon dioxide may inhibit germination or harm the very young root system of the seedling. On the other hand, if it is done on land carrying an established crop, such as an orchard, it will lower the *p*H of the soil; and if the soil is calcareous and very well aerated, it may enable the crop to take up sufficient phosphate and other elements whose availability is very low in these alkaline conditions, to make several months good growth.

Not all the gases present in the soil are in the soil atmosphere: some are dissolved in the soil water. Russell and Appleyard examined the composition of the dissolved gases and found that they consisted mainly

of nitrogen and carbon dioxide, and the dissolved nitrogen could be pumped out much more readily than the dissolved carbon dioxide. No oxygen could be found, presumably because all dissolved oxygen would be immediately used by the soil micro-organisms. Unfortunately no estimates have been made of the distribution of the gases between the liquid and gas phases, but presumably the absolute amount of carbon dioxide, and possibly also the amount relative to that in the gas phase, increases as the moisture content increases; and this may be the cause of the result already noted, that in wet conditions the oxygen content of the soil air falls by much more than the carbon dioxide rises.

The composition of the soil air can only be controlled to a limited extent by the farmer; his control is mainly exercised through varying the porosity, or air space, in the soil, and in particular in the surface layers of the soil, for this controls the rate at which the carbon dioxide produced in the root zone diffuses out into the air. As an extreme example, puddling the surface of a soil when it is wet is a very efficient method for reducing the aeration in the subsoil, and this is an essential operation in much paddy rice cultivation, though its main importance in this example is to reduce the permeability of the soil. But the same effect can sometimes be seen in irrigation practice and perhaps also in ordinary farming. If the surface of a fine-textured soil is compacted, most of the surface pores will hold water against drainage, with the consequence that for several days after it has been well wetted there will only be few empty pores through which the carbon dioxide can diffuse out from the subsoil, so its concentration there will build up considerably. If this happens during a spell of hot weather the absorbing roots of the crop will very soon be killed. This effect is of proved importance in irrigation agriculture, hence the need to lightly cultivate the surface of any such soils as soon after irrigation as possible.[1] And it may be the reason why some farmers in the temperate regions are quite certain that root crops such as sugar-beet benefit from surface hoeing in hot weather, for if a moderately light rain did come it would have much less chance of sealing the soil surface against diffusion of the carbon dioxide from the soil. Further, soils liable to have their surface air space much reduced by rain or irrigation would be expected to benefit from a surface organic mulch, for this maintains the soil surface underneath it in a good crumbly condition.

The main problem facing the farmer in humid regions is that of increasing the oxygen content, and decreasing the carbon dioxide content in the subsoil of heavy or wet soils. This can be done readily in light or medium soils having a high water table simply by draining

[1] For an example, see S. R. Ray and J. B. Shanks, *Proc. Amer. Soc. Hort. Sci.*, 1947, **49**, 420.

them so that the air space is increased down to the capillary fringe above the water table. Draining also improves the aeration of heavy soils, even if it does not appreciably increase the air space of the subsoil, both because it increases the air space in the surface by letting soil rainwater drain through quicker, and also probably in part by preventing the water in the subsoil from becoming too stagnant and the attendant strongly anaerobic condition from arising. This problem is, however, discussed again in more detail on p. 386.

The aeration in the deeper layers of a clay soil are probably very dependent on the amount and depth of the cracks that develop during periods of drought. In tropical climates with a pronounced wet and dry season, or desert soils under irrigation, clay soils will develop cracks 3 feet or more in depth and up to 3 in. wide at the surface, and these cracks may occupy between one-fifth and one-third of the superficial area of the soil.[1] When the rainy season first begins these cracks will maintain adequate aeration for the roots of the crop in the subsoil to continue the function after the surface soil has become impermeable to air.

Only a few methods are available for increasing the number and stability of the channels or cracks going from the surface into the subsoil of impermeable silt and clay soils. If the land is in arable, deep cultivation and subsoiling help, provided the structure of the subsoil is stable so the cracks last for an appreciable time and do not fill up immediately. On the whole, clay soils have stable, and silts unstable, subsoil structure, hence this method is mainly applicable to clay soils. If the soil is not in arable, deep-rooting crops, such as lucerne or even meadow hay in dry years, will open up the subsoil considerably. Very long leys may also encourage an increase in the population of deep-burrowing earthworms, such as *Lumbricus terrestris* and *Allelobophora nocturna*, whose burrows will help the aeration in the subsoil. But the population of these species is usually low in arable land, and their population only builds up slowly when such land is put down to grass (p. 184); hence, it may be found economically worth while to hasten their natural rate of increase by adding a large number of their cocoons to such soils when they are first put down to a long ley after being old arable.

[1] For an example from Egypt, see V. Mosseri and C. A. Bey, *Sultanic Agric. Soc., Bull.* 11, 1923; from Trinidad, F. Hardy and L. F. Derraugh, *Trop. Agric. Trin.*, 1947, **24**, 76.

CHAPTER XIX

THE WATER IN SOILS

Where and How the Water is Held

Soil holds water in two ways: in the interstices or pores or capillaries between the solid particles, and by adsorption on the solid surfaces of the clay and organic matter particles. The mechanism of the adsorption of water on the clay particles has already been discussed in Chapter 8; the mechanism of capillary condensation will be considered here. But at the outset it is important to realise that the water held in even a fairly dry soil cannot be sharply separated into capillary and adsorbed water.

The soil capillaries are not straight uniform tubes, and for that reason it may be best to drop this word and use the words interstices or pores to describe the spaces between soil particles. Soil particles have irregular shapes and so leave irregular spaces between them; they aggregate in crumbs and clods which are separated from each other by spaces; and the soil is filled with channels or tunnels made either by the roots of plants which have since decayed, or by the larger soil fauna, e.g. earthworms and insects. These spaces form an interconnected system filling the whole soil—the pore space of the soil—whose geometry in most soils is characterised by very rapid changes in the width of the space: relatively wide spaces may only connect with other wide spaces through necks which are much narrower.

The water in the soil thus exists in thin films or sheets of very irregular shape and thickness, sometimes bounded by solid particles and sometimes by air menisci. The properties of such thin films, or sheets of water, are dealt with under the heading of capillary phenomena in many books of physics, physical chemistry or colloid science. For the present purpose the following properties of these films are relevant.

Consider a liquid in a capillary tube having a boundary with air. The boundary layer between the liquid and the air is called the meniscus. The meniscus is usually curved; it may make a definite angle —the angle of contact—with the walls of the tube; and it puts the liquid column under a tension T, given by

$$T = \frac{2\sigma}{r} \cos \alpha$$

if the liquid is in a circular tube of radius r, where σ is the surface

tension of the liquid and α is the angle of contact, which is usually zero for the system soil particles-water-air.

This tension which the meniscus exerts on the water column may control the minimum size of pore in which water can exist; for once the tension corresponding to a particular pore size causes a tensional stress in the water that exceeds its cohesion—i.e. the force of attraction between neighbouring water molecules—the water column in the capillary will become unstable. Unfortunately the cohesion of water in fine capillaries cannot yet be measured experimentally or calculated theoretically, so no exact estimate of the minimum size of pore capable of holding water can be made. There is no question that the cohesion of water exceeds 30 atm., so that it can certainly exist in capillaries of 0·1 μ diameter,[1] and R. K. Schofield[2] has collected together evidence to show it almost certainly exceeds 100 atm., corresponding to capillaries of 0·03 μ or about 199 water molecules in diameter, and that it probably exceeds 1,000 atm. Hence there is no theoretical reason against water existing as liquid in capillaries only a few water molecules across.

A study of the detailed processes of adsorption and capillary condensation thus shows that it is not even theoretically possible to divide up the water held by a soil into adsorbed and capillary water for three reasons. Water, unlike alcohols and in particular the long-chain alcohols, does not form a definite monomolecular layer on the clay particles; it has a zero angle of wetting with clay particles and with the adsorbed water films on them, and it can probably exist in capillaries only a few molecules in thickness—so narrow that, for most soils, the water would be in adsorbed multimolecular films. Hence, concepts such as that of hygroscopic water, which is meant to represent the total amount of adsorbed water a soil can hold, are without theoretical foundation.

Suction and *p*F Curves for Soils

The intensity with which water is held by a soil can be measured in units based on the concept of suction. If water rises a height h cm. in a capillary tube standing in water, one can speak of the air-water meniscus exerting a suction of h cm. on the water; alternatively, a suction of h cm. of water must be applied to the base of the tube to suck the water down to the same level as the water outside. Thus water, held by a soil at a suction of h cm., can only be removed from that soil if a suction greater than this is applied to it.

[1] For a recent discussion of the cohesion of water, particularly when it contains some dissolved air, see H. N. V. Temperley and L. G. Chambers, *Proc. Phys. Soc.*, 1946, **58**, 420, 436.
[2] *Trans. 1st Comm. Int. Soc. Soil Sci.*, Bangor, 1938, p. 38.

The intensity with which a liquid is held in a capillary can also be defined in terms of the difference between the free energy of the liquid in the capillary and in bulk. This difference can either be expressed in absolute units, such as ergs per gm., or, as R. K. Schofield[1] has suggested, in the more practical units of a potential difference in the earth's gravitational field, i.e. a height in centimetres, obtained by dividing the absolute units by the acceleration due to gravity; or it can be expressed in a variety of indirect units such as depression of vapour pressure, or freezing-point of the liquid.[2] Schofield also suggested that since the range of free energy changes between a dry, a damp and a wet soil are so large, the logarithm of the free energy difference, expressed in centimetres, which he called *p*F, would be a more convenient unit. The range met with varies from about *p*F 7 for an oven-dry soil through *p*F 4 for a soil in the wilting-point range to about *p*F 2 for a wet soil when well drained.

The suction scale and Schofield's *p*F scale are seen to be two different scales, for the units of suction correspond to a pressure, and therefore involve the density of the water, whereas the units in Schofield's scale do not include this density as they are derived from a free energy difference. These two scales are nearly equal when the soil water is at normal temperature and under a low suction: but they differ to an unknown extent as the suction increases, for very little is known about the density of water in fine pores: it is decreased by the tension which the water is under, but increased in the neighbourhood of the electrical charges on the clay surfaces and of the ions that have dissociated from it into the water; and no determinations are available of the resultant effect of these two opposing tendencies on the density of the water at different moisture contents.

Each scale has its greatest utility in different moisture ranges—the direct suction scale in regions of low suctions, and the free energy and *p*F scales in regions of high suctions, for the simplest method of determining the free energy difference in the low suction region is by a direct determination of the suction that must be applied to move water out of the soil, whilst for the high suction region other methods, such as lowering of vapour pressure or freezing-point, from which free energy differences can be calculated, must be used. The suction range that can be easily covered by direct suction measurements certainly extends up to $\frac{1}{2}$ atmosphere[3] (*p*F 2·7 or 500 cm. of water); and L. A. Richards[4] has shown it can be extended up to 15 atm. (*p*F 4·2). Above about

[1] *Trans. 3rd Int. Congr. Soil Sci.*, Oxford, 1935, **2**, 37.

[2] For a recent discussion of the thermodynamical relationships between these measurements and free energy, see N. F. Edlefsen and A. B. C. Anderson, *Hilgardia*, 1943, **15**, 31.

[3] See L. A. Richards, *Soil Sci.*, 1942, **53**, 241, for the details of his technique.

[4] L. A. Richards and M. Fireman, *Soil Sci.*, 1943, **56**, 395, for suctions up to 2 atm., and L. A. Richards and L. R. Weaver, *J. Agric. Res.*, 1944, **69**, 215, for suctions up to 15 atm.

½ atmosphere, however, indirect methods of measuring suction or free energy differences are usually more convenient to use.

There is no unique relationship between the suction or *p*F of the water in a soil and its moisture content. In the first place, if the moisture content remains constant but the temperature of the soil increases, the suction of the water in the soil decreases, because the surface tension in the air-water meniscus decreases with increasing temperature. An example showing the possible importance of this effect

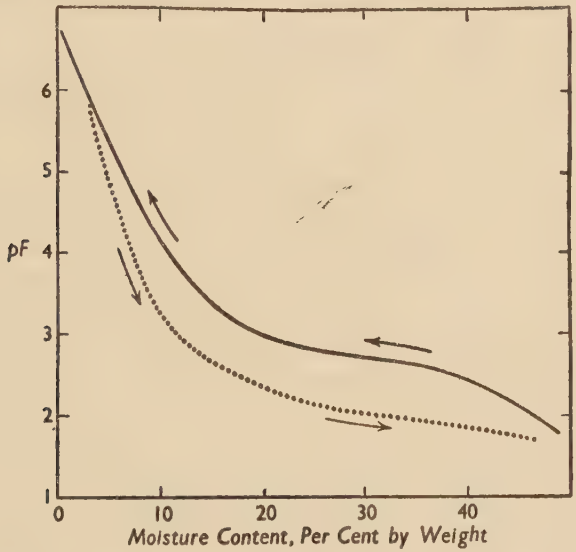


FIG. 33. The *p*F-moisture content curve for a Rothamsted soil.

is given on p. 354. Again, at constant temperature, the suction of the soil water at a given moisture content depends upon whether the moisture content is increasing or decreasing. This can be shown by constructing the suction or *p*F-moisture content curve for a dry soil allowed to wet slowly, and then for the wet soil as it is allowed to dry slowly, as is shown in Fig. 33 for a Rothamsted soil.[1] This figure shows that the wetting and drying curves are different, and hence that there is no unique *p*F-moisture content curve for a soil. The suction or *p*F-moisture content curve also depends on the soil structure in the range of low suctions, as will be discussed in more detail on p. 401.

This dependence of the soil's *p*F-moisture content curve on its past history is due to two causes, one of which gives a fairly reproducible hysteresis loop and the other an irreversible displacement of the curve. The first type can best be studied in a rigid system, i.e. in a system

[1] R. K. Schofield, *Trans. 3rd Int. Congr. Soil Sci.*, Oxford, 1935, **2**, 37.

whose volume does not depend on its moisture content, as, for example, a mass of sand grains in closest packing.[1] In this system the space between contiguous sand particles is connected to its neighbours through necks that have a smaller effective diameter than the main volume of the space. When the moisture content of the sand is falling, i.e. when water is being sucked out of the sand, the effective diameter of the pore is that of its largest bounding neck in contact with the air, for the pore space cannot be emptied of water until the suction is sufficient to break the water meniscus in this neck. On the other hand, when the sand is being wetted the effective diameter of the pore is that of its widest part, for it cannot fill until the meniscus of maximum surface has been created, after which the rest of the pore fills immediately. Thus, the sand holds more water at a given suction when water is being withdrawn than when it is being added.

This hysteresis loop is reversible in the sense that one can take the system round a series of identical wetting and drying cycles and obtain the same hysteresis curve each time. The appearance of this loop for a non-swelling soil block is a sign that the pore space being filled with water has a cellular shape, such as is bound to occur between spherical or irregularly shaped contiguous particles. The existence of this loop has the consequence that the actual moisture content of a soil holding water at a given suction can vary very widely depending on how this moisture content was arrived at. Thus the suction of the water in a soil with a changing moisture content may change appreciably with little alteration in moisture content if the direction of change is reversed.

A second cause for the dependence of a soil's *p*F curve on its past history can only operate when the volume of the soil depends on its moisture content. Swelling involves the constituent soil particles sliding over each other during the process, and the soil particles need not come back into the same relative position with respect to their neighbours after being taken round a wetting and drying, or a swelling and shrinking, cycle. Whenever these shearing movements, set up during drying, result in a repacking of the soil particles, the *p*F or suction curve will be shifted bodily, for the pore space has been irreversibly altered, and in general reduced, by this repacking.

These two types of effect are illustrated in Fig. 34, which shows, for a Rothamsted subsoil, both the typical hysteresis loop and also the bodily shift of the whole curve, consequent upon subjecting the soil particles to the intense suction forces generated by drying the sample to 200° C.[2]

The *p*F curve for a soil gives the pore size distribution in that soil

[1] For a detailed discussion of this system, see W. B. Haines, *J. Agric. Sci.*, 1927, **17**, 264; 1930, **20**, 97; also B. A. Keen, *Physical Properties of the Soil*, London, 1931.

[2] R. K. Schofield, *Trans. 1st Comm. Int. Soc. Soil Sci.*, Bangor, 1938, A, 38.

provided the volume of the soil does not alter with change of moisture content, a condition that is usually only fulfilled in sandy soils. It does not give this information for soils which swell appreciably on wetting; but the concept of a pore size distribution for such soils has no unique significance, for swelling and shrinking can only occur when an appreciable proportion of the soil particles are surrounded by layers of water whose thickness depends on the moisture content of the soil.

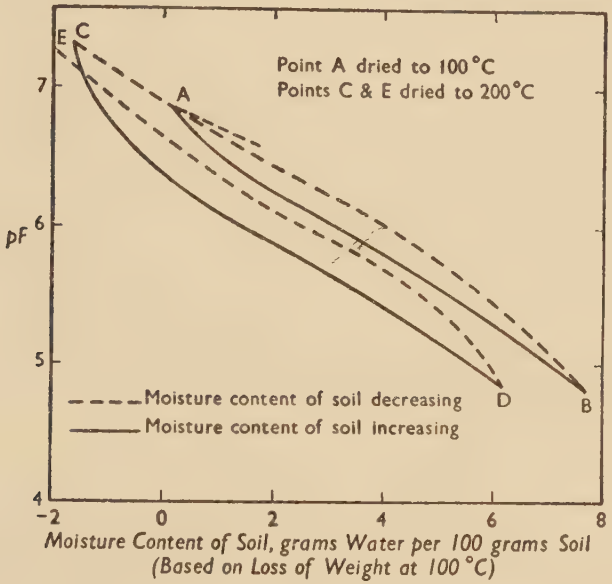


FIG. 34. Hysteresis due to wetting and drying, and to high temperature drying of a Rothamsted soil. The curve was obtained in the direction A B C D E.

Thus, when swelling and shrinking occur, the geometry of the spaces between the soil particles depends on the moisture content.

The suction-moisture content curves for a soil are, in theory, dependent on its tilth or structure. In practice, the dependence on structure, or on the effects of cultivation, is important for suctions under about 20 cm. of water, and very important for suctions much lower than this. In the field, cultivation operations probably barely affect the suction curve for values above 50 cm. of water; but if the soil is brought into the laboratory, air-dried, ground up and passed through a 2-mm. sieve, its suction-moisture content or *p*F-moisture content curve will depend on the method of packing into the measuring apparatus, or its method of being worked before measurement, up to *p*F values as high as 5·4.[1]

[1] M. D. Thomas, *Soil Sci.*, 1928, **25**, 409. He stated his result in the form that the vapour pressure curve for the soil depended on the method of working it for relative humidities above 85 per cent.

The Movement of Water in Soils

Water can move in soils under gravity (drainage) and under a suction gradient (capillarity), and the rate of movement is controlled by the size and continuity of the pores containing the water, by the pressure or suction gradient, and by the viscosity of the water. Water can only move through existing water-filled passages: it cannot move across or down an air space, for it could only do this if it were under sufficient hydrostatic head from above for its weight to break the air-water menisci holding it in the film, so allowing a drop to break off. Thus, water can only move freely in wide pores if water is being applied to the surface. The speed of water movement in a damp soil is thus very dependent on the straightness or circuitousness of the widest continuous water-filled passages and on the thickness of the narrowest parts of these continuous passages, for viscous resistance to flow through narrow passages increases very rapidly as they narrow.[1] Viscous resistance by itself is adequate to explain why water can only move through soils at any appreciable rate if it is moving in relatively thick sheets or through wide pores, and why flow through the main body of a loam or clay soil when wet, or through any soil when partially dry, is so slow as to be of no practical significance.

Entry of Water into a Soil: Infiltration Rate or Permeability

The rate at which water enters a soil, sometimes spoken of as the infiltration rate or permeability of the soil, depends on the proportion of coarser pores in the surface of the soil. It seems probable that rapid movement is confined to pores that are emptied by a suction of 10 cm. of water, though those requiring 40 cm. take some part and possibly also those requiring 100 cm.,[2] corresponding to an "equivalent diameter" of 30 μ.

The rate of entry is thus controlled by every factor which affects the number and stability of these larger pores, and is therefore dependent on the shape of the suction-moisture content curve of the soil in its natural condition at low suctions. It is heavily reduced if the pores at the surface become filled with mud, as may happen if muddy water flows over the land or, during heavy rain storms, if the surface crumbs are not protected from the mechanical shattering effect of fast-falling

[1] The quantity Q of liquid of viscosity η flowing through a tube of internal radius r and length l under a pressure difference p is given approximately by $Q=\frac{\pi pr^4}{8l\eta}$. Hence halving the diameter of the tube reduces the flow sixteenfold.

[2] R. M. Smith, D. R. Browning and G. G. Pohlman, *Soil Sci.*, 1944, **57**, 197. See also G. R. Free, G. M. Browning and G. W. Musgrave, *U.S. Dept. Agric., Tech. Bull.* 729, 1940; L. D. Baver, *Proc. Soil Sci. Soc. Amer.*, 1938, **3**, 52.

heavy drops of water.[1] It may also be reduced if for any reason an appreciable number of these pores become sealed by entrapped air pockets,[2] if the soil crumbs swell appreciably on wetting, and if the subsoil structure of the soil is unstable (see p. 401).

DRAINAGE OF WATER

After all surface water has seeped into a soil, the water redistributes itself by downward drainage, and in many soils this redistribution takes place very rapidly. It can be followed easily in drain-gauges or lysimeters. Thus, the Rothamsted 1/1,000-acre drain-gauge containing 20 inches of bare uncultivated soil, after it has just been filled full of water by a rain storm, i.e. when water is just not standing on the surface of the gauge when the rain ceases, will only lose a third of an inch of water by drainage and nearly all this drainage loss will occur within twenty-four hours, although a trickle of the order of one or two thousandths of an inch a day will go on for a few days longer. This figure of a third of an inch for the total drainage loss gives an estimate for the air content—or to be more exact of the air space that can be filled with water—of the top 20 inches of the fully drained Rothamsted soil, which works out at 1·6 per cent of the total volume. A well-drained Rothamsted soil—like many well-drained heavy loams and clays—does not in fact possess any appreciable volume of air. The Rothamsted gauge containing 60 inches of soil loses 0·43 inch of water in corresponding circumstances, and though most of this loss is completed in two to three days, the gauge continues to discharge water at the rate of a few thousandths of an inch a day for a further two to three days in summer and ten to twelve days in winter.

H. L. Penman and R. K. Schofield[3] have shown that the results are consistent with the idea that the rate of water flow is controlled by the width of the pores and the viscosity of the water, and that flow ceases because of the great viscous resistance to movement in the thin films remaining. Many deep loess and alluvial soils, however, do not show this sharp cut-off of drainage. Thus, W. W. Burr[4] in Nebraska, O. W. Israelson[5] in Utah, and N. F. Edlefsen and G. B. Bodman[6] in California have all worked with soils that continue to show the phenomenon of slow or delayed drainage for many months. Edlefsen and Bodman, for example, heavily irrigated a deep silt loam, protected its surface from evaporation and determined the amount of water in each 6-inch

[1] See J. O. Laws, *Agric. Engng.*, 1940, **21**, 431, for photographs of this effect.
[2] J. E. Christiansen, *Soil Sci.*, 1944, **58**, 355.
[3] *J. Agric. Sci.*, 1941, **31**, 74.
[4] *Nebraska Agric. Expt. Sta., Bull.* 114, 1910.
[5] *Hilgardia*, 1927, **2**, 509; with F. L. West, *Utah Agric. Expt. Sta., Bull.* 183, 1922.
[6] *J. Amer. Soc. Agron.*, 1941, **33**, 713.

layer down to 9 feet at increasing intervals of time after the soil surface had ceased to be water-logged, which was on October 3rd, 1934. Some of their results are given in Table 80, which shows that from the fourteenth to the fifty-eighth day after the commencement of the experiment 4 inches of water had drained out of the profile, of which 1·6 inches had come from the first 4 feet, that drainage almost ceased throughout the winter and spring, but as the soil warmed up in the summer another 5·3 inches left the profile, whilst during the next summer a further 1·3 inches left.[1] This experiment shows that these silt soils can lose water by drainage during warm summer weather two and a half years after an irrigation.

TABLE 80

Inches of Water draining out of a Silt Loam Soil (Davis, Calif.)

Sampling dates	3/10/34–6/10	6/10–17/10	17/10–30/11	30/11/34–8/5/35	8/5–31/8	31/8/35–22/1/37
No. of days of drainage . .	3	11	44	159	115	510
Inches of water draining out of the top 4 ft. of soil . . .	9·6	1·5	1·6	0·2	2·7	0·4
9 ft. of soil . .	17·6	4·1	4·0	0·8	5·3	1·3

The phenomenon of the effect of soil temperature on the amount of water a soil can hold against drainage, which is shown up so well in Edlefsen and Bodman's experiment, is due not only to viscosity but, at least in part, to the effect of temperature on the surface tension of water, as mentioned on p. 349. As the temperature increases the surface tension decreases, hence the pore diameter that can just hold water against a given suction decreases, with the consequence that a volume of water, equal to the pore volume between the two pore diameters, will drain away. Whether this effect is adequate to explain Edlefsen and Bodman's results—and other workers elsewhere have obtained the same result[2]—is not known, as it has not yet been systematically investigated.

The process of the movement of water into soils can be seen clearly when a limited amount of water is allowed to percolate into a deep, dry soil. As the water penetrates, a fairly sharp boundary can be seen

[1] A sampling was made in the spring of 1936, but the results are erratic, as the top layers 0–4 ft. and the bottom layers 7½–9 ft. on the whole appeared to lose water and the middle layers 4–7½ ft. to gain water.

[2] See, for example, L. A. Richards and L. R. Weaver, *J. Agric. Res.*, 1944, **69**, 215; H. Roseau, *C.R.*, 1947, **225**, 320.

moving downwards, the soil being wet on one side and dry on the other. A short time, usually a few days, after water is withheld from the surface the boundary becomes stationary, and this sharp division between unwetted and wetted soil persists for a long time.[1] The reason why the bounding surface persists for so long hinges, once again, on the control viscous resistance imposes on the movement of water, for the water has to flow in very thin sheets from the wet boundary into the dry soil. L. A. Richards[2] has given an example of the slowness of the process: he found it took over three months for equilibrium to be reached when 3 inches of air-dry soil were wetted with water under a suction of 150 cm. (5 feet), though if the soil was previously damp, equilibrium was attained in two to three days. Water can, in fact, only distribute itself through soils at rates as high as a thousandth of an inch per day through an inch of soil if the soil is definitely moist.

FIELD CAPACITY

The moisture content of many well-drained soils falls to a fairly definite value after rain or irrigation has ceased, provided evaporation is prevented, and a soil in this condition is said to be at its field capacity.[3] Some, probably most, soils possessing a well-defined field capacity reach this moisture content in the course of two to three days, when the water in the surface soil appears to be under a suction of 20 to 40 inches, or 50 to 100 cm., though the range of suctions has not been extensively investigated.[4] But soils which show the phenomenon of delayed drainage strongly, such as some deep uniform moderately silty soils, cannot be said to possess a field capacity, for drainage continues to remove appreciable quantities of water from them over periods of several months.

The difference between these two types of soil lies in their pore space distribution. Soils possessing a definite field capacity have two fairly distinct pore space systems—a continuous system of coarse pores extending round the main structural units through which water can

[1] R. E. Moore, *Hilgardia*, 1939, **12**, 383, has described the corresponding effects for the upward rise of water from a water table.

[2] *J. Amer. Soc. Agron.*, 1941, **33**, 778. For another example, see F. Shreeve and W. V. Turnage, *Soil Sci.*, 1936, **41**, 351. Again, F. J. Veihmeyer and A. H. Hendrickson (*Plant Physiol.*, 1926, **2**, 71) packed a 2-ft. long cylinder of soil at field capacity (22 per cent moisture content) between two 2-ft cylinders of the same soil just above its wilting point (14½ per cent moisture content) and found that after 139 days moisture had only moved 6 in. into the dry soil.

[3] Field capacity is here defined as a condition of the soil; but many workers define it as the moisture content, expressed as a weight percentage, at this condition.

[4] If a soil sample is air-dried, and passed through a 2-mm. sieve, and then wetted in some laboratory apparatus, it needs to be put under a suction of 3–10 metres of water (⅓–1 atm.) to bring it down to the same moisture content as the field capacity of the soil in its natural field structure. This does not prove, however, that the water at field capacity in the natural soil is at this suction. See L. A. Richards and M. Fireman, *Soil Sci.*, 1943, **56**, 395, for an example.

move rapidly, and another continuous system of fine pores extending throughout the interior of these units through which water movement is practically inhibited by the viscous resistance to flow in such thin sheets.

The existence of a definite field capacity implies that the rate of water movement under a definite suction gradient, the capillary conductivity of a soil, must fall very rapidly as the suction of the water in a soil increases from about 10 cm. to about 100 cm. This can be illustrated by an example of L. A. Richards.[1] Table 81 shows that the

TABLE 81

Relation between the Suction of Water in a Soil and its Mobility

Suction of water in the soil, cm. of water	Moisture content per cent, air-dry basis	Rate of flow of water under standard conditions[2]
	Sandy Soil	
20·3	13·0	930·0
138·0	6·3	16·4
243·0	5·4	6·95
	Greenville Loam	
32·1	34·0	342·0
161·0	22·4	310·0
248·0	19·9	257·0
393·0	17·2	178·0
597·0	15·4	72·7
	Preston Clay	
14·3	63·3	460·0
27·1	59·0	135·0
149·0	42·2	3·29

capillary conductivity of the Greenville loam, which is a soil possessing no definite field capacity, falls off slowly through the suction range 30 to 600 cm., whilst that for the Preston clay, which possesses a definite field capacity, is reduced a hundred and fifty-fold for an increase of suction from 14 to 150 cm. R. E. Moore[3] has extended this work somewhat and concluded that, on the whole, the capillary conductivity usually sinks to very low values at lower suctions in sands (80 to 90 cm. suctions) than in loams or clays (100 to 140 cm. suctions), and interprets this by saying that the water films become discontinuous, or very thin in places, at lower tensions in sands than in clays; but the generality of this for a wide range of soils has not yet been investigated.

[1] *J. Amer. Soc. Agron.*, 1936, **28**, 297. For a further illustration, see G. J. Bouyoucos, *Soil Sci.*, 1947, **64**, 71.

[2] Capillary conductivity secs. $\times 10^{11}$. The unit of capillary conductivity is 1 cm. water crossing 1 sq. cm. of soil per second under a force of 1 dyne per gram.

[3] *Hilgardia*, 1939, **12**, 383.

Evaporation of Water from a Bare Soil

The rate of loss of water from a damp soil is controlled by the evaporating power of the air and the heat energy falling on it, and so long as the soil can supply water to the surface fast enough to keep it moist, this rate of loss persists. The rate falls sharply, however, as soon as the rate of loss sufficiently exceeds the rate of supply for the surface to become dry, for then instead of the water vapour being produced at the soil surface, and diffusing immediately into the air to be rapidly removed by the air currents, it is produced below the soil surface and must diffuse through the soil pore space under a small concentration gradient before it reaches the atmosphere. Even a dry layer 1 to 2 mm. thick can appreciably reduce the rate of evaporation.[1]

The magnitude and rate of evaporation losses from soils with deep water tables can be illustrated with results obtained during the last seventy years from the fallow drain-gauges at Rothamsted. The rate of loss of the first $\frac{1}{2}$ inch of water is controlled by the evaporating power of the air, and in summer this lasts for about five days, and the rate then drops rapidly from $\frac{1}{10}$ inch per day to about $\frac{1}{12}$ to $\frac{1}{20}$ inch per week, so that it is only after a six-week drought that an inch has been lost by evaporation from the bare soil; and the three-month drought of 1921, which lasted from June to August, only caused a total loss of 1·3 inch,[2] and it is unlikely that more than $\frac{1}{4}$ inch of water moved up from the soil layer below 9 inches in depth into the layer 0–9 inches deep. Fig. 35 illustrates this result for the moisture content of a bare soil at Rothamsted on 27th June, 1870, after a prolonged drought. Within the accuracy of the determination no water had moved up from below 18 inches and only about $\frac{1}{4}$ inch from below 9 inches. The figure also gives the moisture distribution in a neighbouring plot carrying barley, and shows by way of contrast how the crop reduced the water content of the layer 45 to 54 inches deep. The figure further illustrates the importance of specifying the moisture contents on a volume and not a weight basis—a point that will be stressed later on—for the fallow plot happens to have a larger average pore space than the cropped, and hence can hold more water; so that if the comparison was made between moisture contents calculated on a weight basis, the barley would be judged to have removed much more water from the subsoil than it in fact had done.

This result, that a bare Rothamsted soil can only lose about $\frac{1}{2}$ inch of water rapidly by evaporation is not necessarily true in the laboratory, for there H. L. Penman[3] showed that it could lose about $1\frac{1}{4}$ inches at

[1] H. L. Penman, *J. Agric. Sci.*, 1941, **31**, 454.
[2] H. L. Penman and R. K. Schofield, *J. Agric. Sci.*, 1941, **31**, 74.
[3] *J. Agric. Sci.*, 1941, **31**, 454.

the rate of $\frac{1}{10}$ inch per day, that is, at the same initial rate as the drain-gauge on typical June days but for over twice as long. But after it has lost about $1\frac{1}{4}$ inches its rate of loss falls very rapidly to the $\frac{1}{12}$ inch or less per week, just as with the drain-gauge. This behaviour is shown

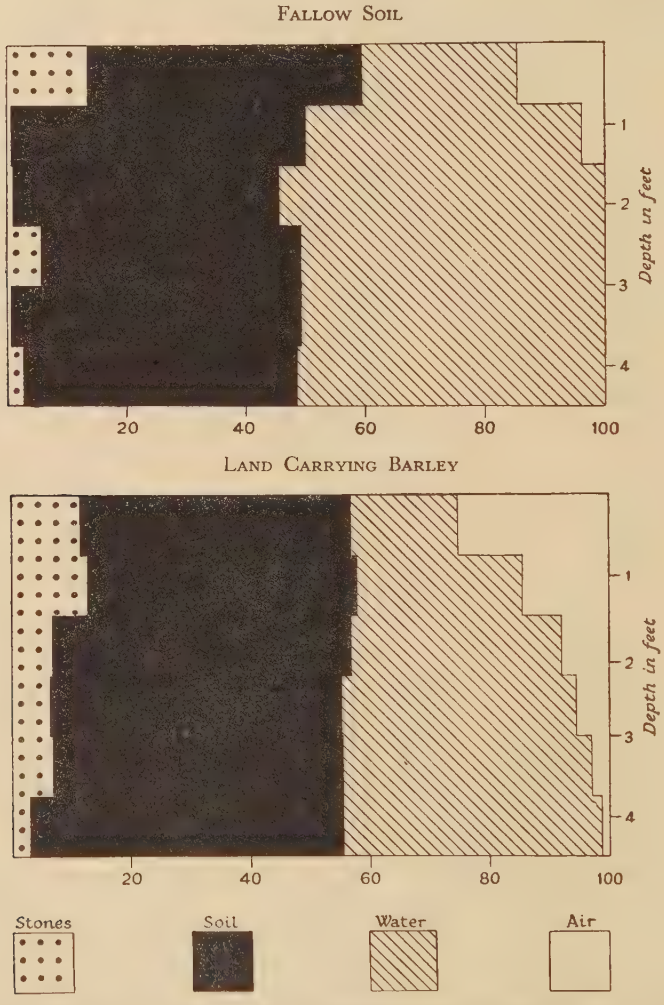


Fig. 35. Volumes of soil, water and air at different depths of a fallow and of a cropped soil at Rothamsted on 27th June, 1870, after a prolonged drought (R. K. Schofield).

graphically by the curve A D in Fig. 40, on p. 383, though in this figure the potential evaporation instead of the number of days is plotted as abscissa, but, as already mentioned, the potential evaporation on a typical June day at Rothamsted is about $\frac{1}{10}$ inch. The differences in

behaviour between the drain-gauge and the laboratory soil is, in fact, due to the effect of high evaporation rates in drying out the soil surface, and in consequence of preventing water moving to the surface at an appreciable rate; for the laboratory results were obtained by keeping the column of soil continuously in a constant-temperature room. But if the surface of this column was heated by shining an electric fire over it for 12 hours a day, to simulate the effect of a sunny June day, the soil then behaved like the drain-gauge soil—it could only lose about $\frac{1}{2}$ inch of water at the rate of $\frac{1}{10}$ inch a day before the rate of loss dropped rapidly to the $\frac{1}{12}$ inch or less per week.

The estimates of the loss of water from a bare soil at Rothamsted are not widely different from those made in subtropical arid climates. R. K. Dravid[1] has given a figure in which the moisture content of a bare soil at different depths is plotted against time for the seven months' dry season at Poona. After four months the surface soil had under 5 per cent moisture, the soil at 4 inches depth 10 per cent, at 8 inches 20 per cent, and at 12 inches 25 per cent moisture. The moisture contents barely altered during the next three months, the main alteration being a slight fall at 4 inches, due to evaporation, and at 12 inches, due to drainage. This loss of water from the subsoil by slow drainage downwards was overlooked by many of the early workers, who concluded, quite wrongly, that this loss of water represented loss by evaporation. A. T. Sen,[2] by following the movements of the soluble salts in the soil, showed quite clearly that at the end of a seven-month drought at Pusa there had been a little upward movement of water from above the three-foot deep level, and a continuous drainage of water out of the soil from below this level; and R. K. Schofield has calculated that the total loss of water by evaporation from this soil during this period did not exceed 2 inches.

A direct consequence of these results is that hoeing a soil, to maintain a dust mulch, cannot appreciably reduce the rate of evaporation of water from the soil once a dry layer has been formed;[3] for the existence of this layer, even if only a millimetre thick, involves the water having to be vaporised below the soil surface and then having to diffuse through the pore space before it can be removed into the atmosphere; and the rate of transfer of water vapour through a dry layer is much slower than the rate of flow of liquid water through a corresponding thickness of damp soil. The rate of loss of water is, in fact, relatively insensitive to the thickness of this dry layer. It is possible, however, that hoeing a wet soil, particularly during periods of slow evaporation,

[1] *Indian J. Agric. Sci.*, 1940, **10**, 352.
[2] *Mem. Dept. Agric. India, Chem. Ser.*, 1930, **10**, 221.
[3] For an example which illustrates this point, see F. J. Veihmeyer, *Hilgardia*, 1927, **2**, 236.

might reduce the loss a little by giving a loose surface which will be able to dry out quicker and hence stop surface evaporation.

The further consequence of these results is that during the winter half-year at Rothamsted, from October to April, the evaporation from the soil is controlled by the evaporative power of the air, or by the amount of radiation received from the sun; for this is sufficiently low, and the rainfall sufficiently frequent, for the soil surface never to be properly dried out. But during the warmer months, from May to September—and even in some years in March, April and October—the evaporation is normally controlled by the number of days the soil surface remains wet, which in turn depends on the frequency of the rain showers and on their intensity, if they are only light, because the showers are usually sufficiently infrequent and the evaporative power of the air, or the energy absorbed by the soil, sufficiently great for the soil surface to be dry for an appreciable number of days per month.[1]

This rainfall distribution effect is of great practical importance in arid countries having summer rainfall, as in the dry farming wheat belt of the Canadian prairies, when summer fallows are taken to store water for a succeeding crop. Frequent light falls of rain on such fallows are evaporated soon after they fall and so cannot contribute to the soil moisture supply. Thus, J. W. Hopkins[2] has computed that at Swift Current, Saskatchewan, if 1 inch of rain falls on one day, $\frac{2}{3}$ inch remains in the soil ten days afterwards, whereas if it falls as five separate showers, each of $\frac{1}{5}$ inch, on five consecutive days only $\frac{1}{3}$ inch remained ten days afterwards.

Evaporation from saline soils differs a little in detail from non-saline soils, for evaporation from them leaves a saturated salt solution, and eventually, a salt efflorescence on the surface. A saturated salt solution, by having a lower vapour pressure than a dilute solution, takes longer to evaporate, and hence longer for the dry surface layer to form; it allows, in fact, solution to move up for a longer time to the surface, and hence more solution to move up than if no salt was at the surface. This has the consequence that once a salt patch has formed in such a soil it grows at the expense of the neighbouring soil, so that instead of a small amount of salt being spread over a large area, it tends to get concentrated in all the hollows of the land, as is illustrated in Plate XXXI. Hence the great importance on all irrigated fields of an absolutely level surface to prevent water standing in pools, and of a water table too deep to influence the moisture régime of the surface soil; for, as will be discussed in Chapter 33, salt accumulation is the constant menace of all arid irrigation projects.

[1] R. K. Schofield and H. L. Penman, *J. Agric. Sci.*, 1941, **31**, 74; H. L. Penman, *Quart. J. Roy. Met. Soc.*, 1940, **66**, 401.

[2] *Canad. J. Res.*, 1940, **18** C, 388.

CHAPTER XX

WATER AND PLANT GROWTH

WATER IS AN essential nutrient for plant growth, and it is needed in much larger quantities than any other; but whereas a large proportion of every other nutrient absorbed by the plant is retained, the outstanding characteristic of the water is its continuous one-way flow from the soil through the roots up the stems into the leaf surface, where it is evaporated mainly inside the stomata, through which it diffuses into the air.

The rate at which water is transferred from the soil into the air by the plant is controlled by four separate processes: the transfer of water from the soil through the protoplasm of the cells of the absorbent rootlets into the vascular system; the transfer from the vascular system through the protoplasm of the leaf cells bounding the stomata; the energy supply falling on the leaves that can be used for evaporating the water in the stomata and from the surface of the leaf; and the transfer of the water vapour from inside the stomata into the main body of the air by diffusion and convection. The transfer of the water up the vascular system from the rootlets to the leaves always appears to be more rapid than its transfer through the protoplasm of living cells, so never controls the speed of water movement. Plants growing in damp soil under normal English summer conditions usually have their rate of water loss controlled either by the amount of energy available for evaporating the water or by the rate of diffusion of this vapour into the air: they normally transfer water from the soil to the leaf cells faster than it is dissipated from the leaves as vapour. But under conditions either of high evaporation, due to strong sunlight or hot drying winds, or of limited water supply in the soil, the root cells may no longer be able to transfer water from the soil to the vascular system as fast as the leaf cells are dissipating it: the leaves will then begin to lose water, causing those of many species to lose turgor and wilt.

Shortage of water in the leaf has several effects besides causing it to wilt: the stomata close almost entirely, thus cutting down transpiration losses, but also photosynthesis, very considerably—and this is normally the first effect to be manifest; the leaf cells lose water, causing first the osmotic pressure of the cell sap to rise, and later the death of the cells, and hence of the leaf.

Most farm crops react to prolonged drought by shedding their leaves,

thus reducing the amount of water they transpire and hence their demands on the soil water; but they differ very considerably in the severity of drought they can withstand before all the leaves have been lost or have died. All young plants are very dependent on an adequate supply of water and are unable to withstand any appreciable drought; but as the plant grows older, it can usually survive periods of water shortage without any serious injury, particularly if the drought occurs during overcast weather. It is only during the later stages of growth that marked differences in the ability of different crops to withstand drought become important. Sorghums, such as durra, kafir and milo —the characteristic summer cereals of the semi-desert—can, when well established, withstand droughts that would kill most semi-humid crops, because their leaves are so constructed that they can become dormant during spells of weather hot and dry enough to kill the leaves of non-desert crops.

The direct effect of drought on a crop is thus fundamentally on the amount of leaf the crop is able to carry. Its effect can be well studied on cereals, for their growth in many parts of the world is limited by water shortage. Moderate drought on an established cereal crop can cause an appreciable loss of leaf, and hence of straw, without any great loss of grain, though it tends to bring the crop to maturity earlier. As the drought becomes more severe the crop will come to maturity increasingly earlier and the grain yield will fall more rapidly than the straw, until a condition is reached when there is not enough water for the crop to form any grain. On the other hand, if a crop grown under moderately dry conditions is irrigated, increasing the amount of the irrigation water will increase the amount of leaf, and hence the straw yield much more than the grain, as is shown by some experiments of J. A. Widtsoe,[1] given in Table 82.

TABLE 82

Yield of Wheat with Increasing Quantities of Irrigation Water (Greenville Farm, Utah)

Irrigation water: inches	5	7·5	15	25	50
Yield of grain, cwt. per acre	19·7	21·3	22·8	23·0	23·5
Yield of straw, cwt. per acre	25	28	33	37	48
Ratio grain/straw . .	0·80	0·76	0·69	0·63	0·49

Average rainfall during growing period, 5·0 in.

The effect of water above the minimum required to allow a normal plant to develop depends on the time at which this additional water is

[1] *Utah Agric. Expt. Sta., Bull.* 116, 1912.

given. When the plant is young the extra water is not only usually wasted, but may have incidental harmful effects on the soil structure and the air supply to the roots. This is illustrated by the results of some experiments of A. T. Bartel and C. Hobart[1] with wheat in the arid Salt River Valley of Arizona, which are given in Table 83. They show that water in excess of 6 inches, of which 3 inches came from rainfall, early in the life of the crop appears to be harmful, whilst during the period of maximum growth, from the commencement of rapid shoot growth until the soft dough stage of the grain, the crop has a very considerable water demand. This harmful effect of excess

TABLE 83

Effect of Distribution of Irrigation Water on Yield of Wheat
(Salt River Experiment Station, Arizona)

Inches of irrigation water given up to tillering	3	6	3	9	6	12
Inches given after tillering	15	12	9	9	6	6
Yield of grain, bushels per acre	43	39	39	37	34	30
Yield of straw, cwt. per acre	66	56	57	46	46	39

Average rainfall for the three months before tillering, 3·0 in.; and for the three months from tillering to harvest, 0·5 in.

irrigation water can be seen on the yield of a perennial crop such as lucerne hay, and two examples from California are given in Table 84. Clearly, water in excess of 36 to 42 inches in unnecessary, and the efficiency of each inch of water used, up to 30 inches on the heavier and 36 inches on the lighter soils, either remains constant or slightly increases.

These results appear to be fairly clear cut, but the optimum supplies of water found in these experiments may be in excess of the plant's needs owing to the difficulty of ensuring uniform penetration of the water, and it is probable that the same maximum yields could have been obtained with less water if it had been uniformly sprayed over the crop. Many field experiments have, in fact, given less consistent and reliable results due to the large number of complicating factors that can enter, and many examples showing the very variable response of the crop to additional irrigation water can be found in B. A. Etcheverry and S. T. Harding's book on Irrigation Practice.[2]

The water supply affects the amount of nutrients taken up by the plant, for as it increases so does the adsorption of mineral matter,

[1] *Arizona Agric. Expt. Sta., Bull.* 151, 1935. [2] Vol. I, 2nd ed., New York, 1933.

particularly calcium, increase, as is shown for wheat in Table 85.[1] On the other hand, the uptake of nitrogen appears to be almost independent of the water supply, so that since the yield increases with increasing water supply, the nitrogen content of the plant decreases, and this decrease is reflected in both the grain and the straw.

TABLE 84

Effect of Amount of Irrigation Water used on Yields of Lucerne Hay (California)

Soil	Fine sandy loam[2]		Fine sand[3]	
Inches of water supplied	Inches of water per irrigation	Yield, tons per acre	Inches of water per irrigation	Yield, tons per acre
0	—	3·9	—	—
12	6	5·6	4	5·3
18	6	6·8	6	5·7
24	6	7·9	6	6·3
30	7·5	9·0	6	7·2
36	9	9·3	6	8·2
42	—	—	7	8·7
48	12	9·0	8	8·4
60	15	8·4	10	8·2

TABLE 85

Percentages of Nitrogen, Ash, Phosphorus, Potassium, Calcium, and Magnesium in Wheat Grain Grown under Irrigation (Logan, Utah)

Amount of irrigation water	Calcium		Magnesium		Nitrogen		Phosphorus		Potassium		Ash	
	Per cent	lb. per acre	Per cent	lb. per acre	Per cent	lb. per acre	Per cent	lb. per acre	Per cent	lb. per acre	Per cent	lb. per acre
None	0·103	2·31	0·170	3·82	2·39	53·82	0·295	6·64	0·396	8·92	1·56	35·12
5 inches	0·107	2·02	0·171	3·54	2·16	44·88	0·301	6·38	0·414	8·97	1·56	34·17
10 ,,	0·122	2·63	0·172	3·65	2·18	47·14	0·306	6·38	0·439	9·49	1·57	35·90
15 ,,	0·165	3·53	0·172	3·23	1·99	42·38	0·323	6·87	0·491	10·47	1·71	36·38
20 ,,	0·195	3·78	0·198	3·77	1·98	37·75	0·371	7·08	0·490	9·35	2·01	38·45
35 ,,	0·211	4·72	0·207	4·64	2·01	45·12	0·458	10·24	0·534	11·95	2·28	51·13
67·5 ,,	0·262	5·64	0·224	4·80	2·06	44·70	0·424	9·12	0·535	11·50	2·19	47·13

[1] J. E. Greaves and E. G. Carter, *J. Biol. Chem.*, 1923, **58**, 531. See also J. E. Greaves and D. H. Nelson, *J. Agric. Res.*, 1925, **31**, 183.

[2] S. H. Beckett and R. D. Robertson, *Calif. Agric. Expt. Sta., Bull.* 280, 1917.

[3] S. H. Beckett and M. R. Huberty, *Calif. Agric. Expt. Sta., Bull.* 450, 1928.

This result is of special interest for wheat and barley, since the nitrogen content of the grain affects their market value: high nitrogen content in wheat usually gives a strong flour and a good loaf, whilst low nitrogen content in barley usually gives a good malt and a bright beer. General field experience shows, in accordance with this rule, that the quality of a given variety of wheat is usually highest in dry years and of barley in wet ones. Thus, in C. H. Bailey's[1] examination of the data for spring wheat, gathered in sixteen counties of Minnesota, the results were:

Rainfall: Apr. 1–Sept. 1, inches	12–14	14–16	16–18	18–20	20–22	22–24
Nitrogen, per cent in grain .	2·62	2·41	2·14	2·35	2·26	2·04

and in F. T. Shutt's[2] comparison of wheat grown under irrigation at Invermere, British Columbia, and under dry land conditions at Lethbridge, Alberta, the percentages of protein in the wheat grain were:

	1st Year	2nd Year	3rd Year
Irrigated . . .	14·02	16·93	13·91
Dry Land . . .	16·70	18·47	18·18

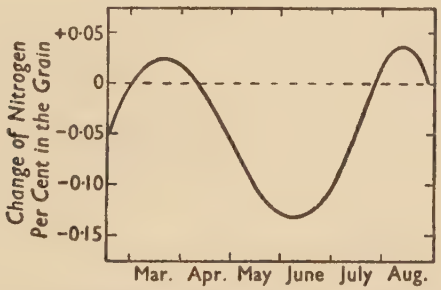


Fig. 36. The effect of an additional inch of rain above the average in any month on the nitrogen content of barley grain at Woburn.

In England the nitrogen content of barley grain is reduced by rain falling during the growing season, particularly in May and June, as is shown in Fig. 36;[3] the relation between these two is, in fact, sufficiently close for a reasonable forecast to be made of the nitrogen content of the grain about two months before harvest.[4]

The Amount of Water Transpired by a Crop

Much interest has been taken in determining the weight of water a plant must transpire to produce a unit weight of dry matter in its

[1] *Minnesota Agric. Expt. Sta., Bull.* 131, 1913.
[2] *Trans. Roy. Soc. Canada*, 1935, **29**, Sect. 3, 37.
[3] E. J. Russell and J. A. Voelcker, *Fifty Years of Field Experiments at the Woburn Experiment Station*, London, 1936.
[4] E. J. Russell and L. R. Bishop, *J. Inst. Brew.*, 1933, **39**, 287.

aerial parts, i.e. excluding the dry matter in the roots; and this weight of water has been called the transpiration coefficient or ratio of the crop. As long ago as 1850 J. B. Lawes[1] published the results of some experiments made at Rothamsted, in which he found that wheat, barley, clover, beans and peas all used about 200 to 270 lb. of water for each pound of dry matter produced, and subsequent workers in western Europe have obtained similar figures.[2] On the other hand, workers in the semi-arid regions of the U.S.A. have found much higher values, as is shown in Table 86, which summarises many results obtained by L. J. Briggs and H. L. Shantz[3] at Akron, Colorado. These variations clearly show that plants do not have unique transpiration coefficients.

TABLE 86

Transpiration Coefficients of Various Crops in Colorado

Crop	Extreme values for different varieties	Mean value for crop
Proso	268 to 341	293
Millet	261 to 444	310
Sorghum	285 to 467	322
Maize	315 to 413	368
Wheat	473 to 559	513
Barley	502 to 556	534
Oats	559 to 622	597
Flax	—	905
Sugar-beet	—	397
Potato	—	636
Cow-pea	—	571
Clover	789 to 805	797
Lucerne	651 to 963	831
Grasses	—	861
Various native plants (i.e. weeds)	277 to 1076	—

The amount of water transpired by a crop is controlled by the meteorological conditions prevailing—the rainfall and the evaporating power of the air—rather than by the amount of growth it makes. An extreme example of this is furnished by some results obtained on the permanent hay plots at Rothamsted in 1870. The spring was very dry—the rainfall during the period April to June being only 2·8 inches —which is well under half the average for this period. The amount

[1] *J. Hort. Soc. London*, 1850, **5**, 38.

[2] For a very full review of the results obtained before 1913, see L. J. Briggs and H. L. Shantz, *U.S. Dept. Agric., Bur. Plant Indust., Bull.* 285, 1913, and for a more recent summary, see C. H. Lee's contribution in *Physics of the Earth*—IX *Hydrology*, ed. by O. E. Meinzer, New York, 1942.

[3] *J. Agric. Res.*, 1914, **3**, 1. See also H. L. Shantz and R. L. Piemeisel, ibid., 1927, **34**, 1093.

of water left in the soil shortly after the hay harvest was determined on three plots: that receiving no manure and which yielded $5\frac{3}{4}$ cwt. of hay per acre, about a quarter of its average yield; that receiving complete minerals and about 80 lb. of nitrogen as ammonium salts each year and which yielded 30 cwt. of hay, about a half of its average yield; and that receiving complete minerals and about 85 lb. of nitrogen as nitrate of soda each year, and which yielded 56 cwt. of hay, about its average yield. The water deficit in the soil, i.e. the amount of water the crop took from the soil over and above that received during the growing season from the rain was, however, surprisingly independent of the yield of hay; it was about 3 inches, confined to the top 27 inches of soil, on the unmanured plot and about 4 inches, confined to the top 36 inches of soil, on the manured.[1] Thus, the nitrate of soda crop used about 7 inches of water—3 inches from the rainfall and 4 inches from the soil—to produce 56 cwt. of hay, whilst the unmanured crop used about 6 inches of water—3 inches from the rainfall and 3 inches from the soil—to produce just one-tenth the weight of herbage; and the reason it did not transpire the extra inch of water is probably because it was too starved to send its roots down as deep as the manured plants did, so its leaves were dying or dead when those of the manured plants were transpiring the last inch. This result appears to be out of line with the general result of arid farming, namely, that unmanured grain crops are more drought-resistant than those fully manured, but the explanation probably lies in the reduced drought resistance of the more succulent leaves of the manured crop rather than in its increased water demands.

The amount of water a crop transpires depends on the amount of water available to the crop, on the period of the day in which the stomata of the leaves of the crop are open, and on the solar energy falling on the crop. For turgid crops with open stomata, the amount of water transpired depends on the energy available, for most of the energy absorbed by the leaves that is not reflected or re-radiated is used to evaporate water.

H. L. Penman[2] has shown that it is possible to calculate the amount of water evaporated from an open water surface or a wet, bare soil or an actively growing crop from considerations of the energy balance and the evaporative power of the air at the evaporating surface, and he has derived equations connecting the rate of evaporation with data obtained or obtainable by meteorological observations. Of the solar energy falling on a wet surface, part is reflected back, part is re-radiated

[1] J. B. Lawes and J. H. Gilbert, *J. Roy. Agric. Soc.*, 1871, **7**, 1. The figures given here have been recalculated on a volume basis by Dr. R. K. Schofield, to whom I am indebted for them.

[2] *Proc. Roy. Soc.*, 1948, **193** A, 120.

as long-wave radiation (see p. 328), part is used to heat up the absorbing material and the air around it, part is used in photosynthesis, and the remainder evaporates water at the rate of approximately 1 gm. per 590 calories, the exact amount depending on the surface temperature of the leaf. The part used by crops for photosynthesis is negligible, being about one-half of 1 per cent. The part used for heating the soil or the plant itself is small if taken over a period of several days, though not over shorter periods (see p. 334). The part reflected back can be determined experimentally, and the parts re-radiated as long-wave radiation and used to heat the air can be approximately calculated from meteorological observations. Again, the power of the air to carry away the water vapour that evaporates from the wet surface depends on the temperature of the evaporating surface, on the temperature and water vapour content of the air, and on its rate of movement over the surface; and it can also be calculated approximately from meteorological data.

Penman made the calculation in three ways, and has given semi-empirical results so that they could be expressed in terms of quantities that are either measured by meteorological stations or could be so measured. The simplest of his results connects the evaporation E from an open water surface with the speed of the wind and the saturation deficit of the air, namely:

$$E = 0{\cdot}35\ (e_s - e_d)\ (1 + 0{\cdot}0098u_2) \text{ mm. per day}$$
$$\doteqdot 0{\cdot}37\ (e_s - e_d)\ B \text{ mm. per day}$$

where e_s is the vapour pressure of the water at the water surface, e_d is the vapour pressure of the air in bulk at the dew-point, u_2 is the speed of the wind 2 metres above ground-level in miles per day, and B is the mean force of the wind on the Beaufort scale. The quantity most difficult to measure, and least commonly measured is e_s, which depends on the temperature of the water surface. For a crop e_s depends on the temperature of the transpiring leaf, and is not only a quantity very difficult to measure, but also varies with the position of the leaf on the plant. One could determine a mean exposed leaf temperature; but this problem can be circumvented, as this term can be eliminated and replaced by the vapour pressure of saturated air at the mean air temperature, a quantity that can easily be determined, but the resulting equation is far more complicated than the simple one given above.

These calculations give results for the amount of water evaporated from an open water surface or a wet, bare soil that are in satisfactory agreement with observation, considering the limitations of the equations used. However, if applied directly to a growing crop they give transpirations definitely in excess of those observed. Thus, the actual

transpiration from turf is only about 80 per cent of the computed in summer, about 70 per cent during the spring and autumn, and about 60 per cent in winter. This difference is due to the behaviour of the stomata. When the stomata are open, the leaf behaves as an open water surface because the rate of removal of water vapour from the surface of the leaf into the body of the atmosphere is usually slower than the rate of diffusion of water vapour through the stomatal openings, even though they only occupy 1 to 3 per cent of the leaf area. This is the normal condition of a turgid leaf during the day-time. But at night-time the stomata close, and then the resistance to the diffusion

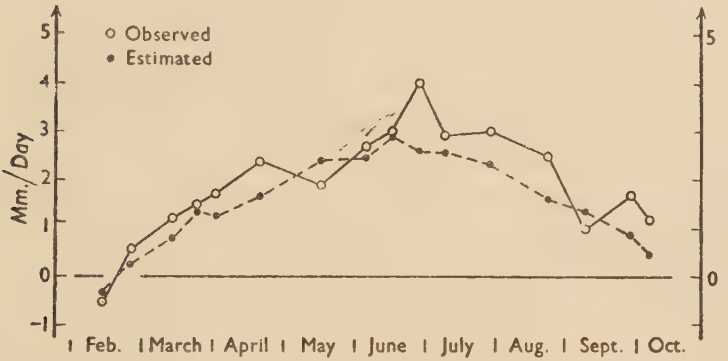


FIG. 37. The observed and computed evaporation from a turf soil at Rothamsted. (Water table 16 in. below the surface.)

of water vapour from the inside of the leaf to the outside limits the rate of transpiration. Hence, the shorter the hours of daylight, the shorter the proportion of the day that the leaf behaves as an open water surface, and the greater the difference between the amounts of water lost by an open water surface and the crop, in accord with Penman's findings. Fig. 37 gives an example of the concordance between the measured and the calculated transpiration from a turf surface at Rothamsted, and also of the difficulties of making an accurate calculation because the divergence between the two curves could easily be due to inaccuracies in the estimates of some of the physical quantities in the equation.

A consequence of Penman's work is that the transpiration from an actively growing, or a turgid, crop is primarily dependent on meteorological conditions, and only dependent on the crop in so far as the behaviour of stomatal openings and closing vary. But this calculation is only valid if the crop covers an appreciable area of land: it is not valid for individual plants in isolation nor for crops in small areas with unusual exposures. It enables one to compute, from standard

meteorological data, the amount of water a turgid crop will transpire; and the values so calculated for the average seasonal transpiration of a turgid crop at Rothamsted are given in Table 87, along with the average rainfall and drainage through a bare soil.

TABLE 87

Evaporation from a Bare Soil and Transpiration by Grass at Rothamsted

(Average for 1931–40)
In inches of water

	Rainfall	Drainage through bare soil	Evaporation from bare soil	Calculated transpiration	Rainfall minus transpiration
Winter (4 months), Nov. to Feb.	10·8	8·6	2·2	0·5	10·3
Spring, March–April	4·0	1·8	2·2	2·7	1·3
Autumn, Sept.–Oct.	5·2	2·1	3·1	2·1	3·1
Total for the 4 equinoctial months	9·2	3·9	5·3	4·8	4·4
Summer (4 months), May–Aug.	8·2	2·0	6·2	12·9	—4·7
Total for year	28·2	14·5	13·7	18·2	10·0

The table shows that a deficit is built up under a continuously growing crop in the summer, which is not made up on the average until some time in November. The figures given for the transpiration are, however, a little uncertain, particularly for the winter period, where the transpiration is probably somewhat under-estimated, but they are of the right order of magnitude, for D. Lloyd[1] has calculated, from rainfall and river discharge data, that the average annual evaporation and transpiration from the watershed of the Lea, near which Rothamsted is situated, is about 19 inches, though this estimate is known to be a little too high, as not all the rain-water entering the ground-water under the watershed finds its way into the river.

The table also allows one to calculate how much water a crop must be able to take from the soil to remain turgid for any specified seasonal rainfall, or, alternatively, how much water must be removed by drainage.

One consequence of the amount of water used by crops depending primarily on the energy supply or the evaporative power of the air, is that all the water falling on the crop, whether as light drizzle or dew

[1] *Quart. J. Roy. Met. Soc.*, 1941, **67**, 33.

or whether as a definite rain storm, is as effective in contributing to the water requirements of the crop as is the water removed from the soil. There is no question here of light showers contributing nothing to the water requirements of the crop, in the way that they usually contribute nothing to the water supplies of the soil—every thousandth of an inch of rainfall, however long it takes to fall, on being evaporated from the plant leaves or stems reduces the plants' demands on the soil water by this amount.

The total water used by different plants or crops in a year depends on the periods at which crops are making active growth: broad-leaved evergreen crops near a water table, or in a high rainfall region, will transpire more water per year than deciduous crops or crops which are only growing for short periods of the year, and then either mature or become dormant. C. H. Lee[1] has collected together many different estimates of the amount of water actually transpired by crops. They reach 5 to 6 feet a year for evergreen trees and marsh grasses in tropical swamps and river bottoms, such as in the Nile Sudd, and are about 24 to 36 inches for perennial crops, such as lucerne and pastures, in the typical irrigated areas of the world, and about 18 to 30 inches for short season crops, such as the small grains and deciduous orchards.

Plants can transpire up to $\frac{1}{4}$ inch of water in a summer's day at Rothamsted, and they will certainly transpire more than this in hot, dry climates. In Saskatchewan[2] wheat can transpire 0·2 inch of water daily over a seventy-day period, and in windy weather during the heat of summer up to 0·3 inch a day.

Some of the methods employed for reducing the effect of droughts are immediately obvious from these results. The earlier in summer a crop matures the less water it will need, as it will be maturing at a time of high or increasing daily water demands. Crops growing throughout the summer and maturing in autumn, e.g. sugar-beet in this country, will tend to have heavy water demands, as they have to grow throughout the period of maximum transpiration; and for these crops early maturity is of limited value, as it will only save days in late autumn, a period of rapidly decreasing daily water demands. Permanent crops, such as pastures and leys, make the heaviest demands of all if they are to grow throughout the year, which they can only do if the annual rainfall is in excess of the transpiration, and also if a considerable proportion of it falls during the summer months.

[1] Chapter VIII, *Hydrology*, ed. O. E. Meinzer, 1942.
[2] *Soil Res. Lab., Swift River, Sask., Rept.*, 1943.

CHAPTER XXI

THE TRANSFER OF WATER FROM SOIL TO PLANT

The Wilting Range in Soils

THE ROOTS OF the plant supply it with the greater proportion of the water it uses during its lifetime, hence the rate the root system can extract water from the soil during dry periods is of fundamental importance in the development of the crop. During hot, dry weather the leaves of many plants wilt whenever water is not being supplied to their cells quick enough: they can wilt at midday in hot sunny weather when the plants are growing in damp soil because water cannot pass through the protoplasm of the root and leaf cells quickly enough, but they normally recover turgor early in the afternoon under these circumstances; or they can wilt because the roots cannot move water out of the soil quickly enough, in which case they may not recover turgor until the late afternoon or evening. As the soil around the roots becomes drier, water moves into the roots more slowly, and it takes longer for the leaves to regain their turgor, until a time is reached when first the mature leaves and later the younger leaves cease to regain turgor before transpiration begins again next day.

Plant roots can only extract water from a soil if they can apply a sufficiently great suction to move it out of the pore space. As the soil dries, so the suction needed to extract water rises and the rate of movement of water into a given length of root decreases, which may sometimes have the consequence that if the crop is growing in conditions conducive to high rates of transpiration, the actual maximum rate it can reach will decrease as the soil dries.[1] The maximum suction roots can exert on the soil water does not appear to be a very definite quantity, but if the water is held at suctions higher than about 7 atm.[2] —the first permanent wilting-point of the soil[3]—the roots appear to be unable to extract sufficient water to keep the whole plant of most farm crops turgid when placed in a saturated atmosphere, i.e. in an atmosphere where transpiration cannot take place; and if above about 20 to 30 atm.—the ultimate wilting-point—to keep any leaves turgid. The water held between these two suctions is

[1] S. I. Dolgov, *C.R. Acad. Sci. (U.S.S.R.)*, 1947, **55**, 449.
[2] L. A. Richards and L. R. Weaver, *J. Agric. Res.*, 1944, **69**, 215.
[3] J. R. Furr and C. A. Taylor, *U.S. Dept. Agric., Tech. Bull.* 640, 1939; J. R. Furr and J. O. Reeve, *J. Agric. Res.*, 1945, **71**, 149.

sufficiently available to the roots for the maintenance of life, but not for growth; that held at suctions less than that corresponding to the first permanent wilting-point may be, but is not necessarily, readily available for growth.

This conception of a permanent wilting range in the soil has not been used by all workers, although L. J. Briggs and H. L. Shantz, in their classical paper[1] on the subject, clearly stated that such a range exists; they defined the wilting coefficient of a soil as the moisture content that would no longer support plant growth: most plants growing in drier soil than this could still extract enough water to maintain life.

The great difficulty of determining any permanent wilting-point for a soil lies in the uncertainty of deciding exactly when the plant remains wilted in a saturated atmosphere. The difficulty, however, is of less importance than one might expect, for the moisture content of most soils does not vary very much between suctions of 10 to 20 atm., or roughly between *p*F 4·0 and 4·3. Nor does the wilting-point depend very much on the plant, for again, although the maximum suctions different plant roots exert differ somewhat, this does not greatly alter the moisture content at which wilting takes place for the same reason. The suction at wilting-point is commonly taken as either 15 atm.,[2] or *p*F 4·2[3] (16 atm.), and it must be accepted with the provisos that there should be a fairly rapid drop in the availability of the soil water to the plant in the neighbourhood of this suction; that no two observers necessarily agree exactly when a plant has reached its wilting-point; and that different plants exert different suctions before they reach their wilting-points.

The discussion in the previous paragraphs has implicitly assumed that the water in the soil is present as pure water; but in fact it contains dissolved salts, which cause it to have an osmotic pressure. The osmotic pressure of a solution is the pressure one must exert to force pure water through a membrane permeable to water but not to salts into the solution. The cell sap in the roots also contains dissolved substances, so can exert an osmotic pressure against pure water, and the root can only extract water from the soil if the osmotic pressure in the root cells is appreciably higher than that in the soil solution, which is the name given to the water in the soil. This fact must not be taken to mean that the transfer of water from the soil solution to the plant root is purely an osmotic phenomenon, for it only takes place if the roots are properly aerated, implying either that the roots expend energy in making the transfer or in maintaining their semi-permeable membranes.

[1] *U.S. Dept. Agric., Bur. Plant Indust., Bull.* 230, 1912.
[2] L. A. Richards and L. R. Weaver, *Soil Sci.*, 1943, **56**, 331.
[3] See J. V. B. da Costa, *J. Agric. Sci.*, 1938, **28**, 630, for a discussion on this figure.

Now the osmotic pressure of the cell sap of agricultural crops appears to be between 10 and 20 atm., and is probably rather higher for plants that have been growing in conditions of water shortage or in solutions having an appreciable osmotic pressure than for those that have been growing with a good supply of fairly pure water. Now no crop can make any appreciable growth in a solution having an osmotic pressure of 10 atm., and some crops have their growth affected if the osmotic pressure of the solution exceeds 2 atm., and their growth may be reduced in proportion as the osmotic pressure rises from 2 to about 10 atm.[1]

The osmotic pressure of the soil solution depends on the amount of salt and the amount of water present in the soil; hence, as the soil dries, so the osmotic pressure of the soil solution increases. For normal soils in the temperate regions the osmotic pressure of the soil solution at the wilting-point is under 2 atm., although it may be above this on sandy soils which have been given large dressings of soluble fertilisers, as happens sometimes in intensive market-garden areas.[2] But in many semi-arid areas the soil may contain enough salts for the osmotic pressure of the soil solution to be well above 2 atm. even when the water is held at a suction well below the 15 atm. of the normally defined wilting-point.

The soil water is only at a suction of between 10 to 15 atm. or over in a soil carrying a permanently wilted crop if the osmotic pressure of the soil solution is low. If it is appreciable, the plants wilt permanently when the soil water is at lower suctions than this. The ease with which plant roots extract water from the soil seems to depend, not on the suction of the water in the soil, but on its free energy; and these two are only equivalent when the water contains no dissolved substances. The free energy of a solution in a soil is approximately the sum of the free energy change due to the dissolved salts and that due to the curved air-water menisci bounding the solution in the soil pores. Both of these quantities can be measured in units of atmospheres. Hence, if the osmotic pressure of the solution is 3 atm., and it is under a suction of 3 atm. in the soil pores, then plant roots will have at least the same difficulty in using the water from this solution as they would if the soil contained pure water at a suction of 6 atm.

Some work of C. H. Wadleigh and his co-workers illustrates these points well. Thus Fig. 38[3] shows the effect of the free energy of the water supply on the growth of beans. The plants were grown in a loam soil to which no sodium chloride or 0·1, 0·2 or 0·4 per cent of

[1] F. M. Eaton, *J. Agric. Res.*, 1942, **64**, 357; O. C. Magistad and R. F. Reitemeier, *Soil Sci.*, 1943, **55**, 351; C. H. Wadleigh and A. D. Ayers, *Plant Physiol.*, 1945, **20**, 106.

[2] L. M. White and W. H. Ross, *J. Agric. Res.*, 1939, **59**, 81.

[3] With A. D. Ayers, *Plant Physiol.*, 1945, **20**, 106.

sodium chloride had been added, and were watered when the average moisture content of the soil had fallen half-way, two-thirds way and nine-tenths way from field capacity to the wilting-point, as determined in the salt-free soil. Again, they showed[1] that beans, maize, lucerne and cotton could extract water from soils with free energy reductions of 8 to 9, 10·5 to 11·5, 12 to 13 and 16 to 17 atm. respectively when

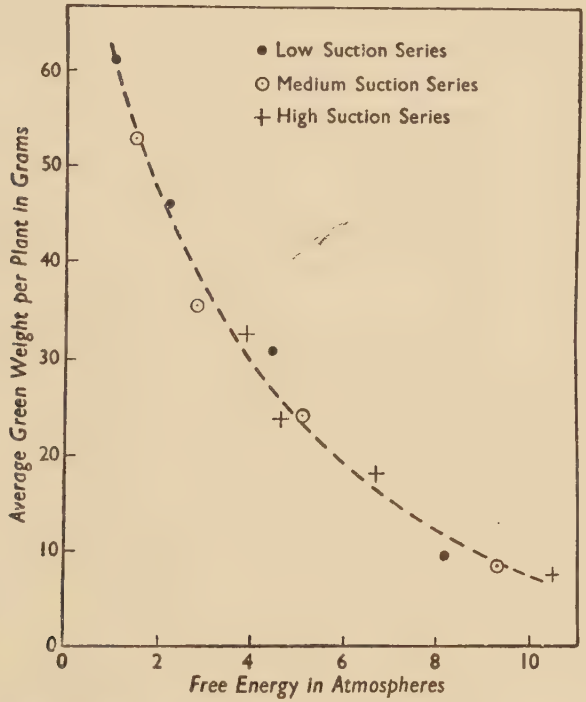


FIG. 38. The relation between the green weight of beans and the mean free energy of the water supply.

only about 2 atm. was due to the suction with which the soil held the solution, and the remainder to the osmotic pressure caused by the dissolved salts, in this case sodium chloride at concentrations of 0·1, 0·15, 0·25 and over 0·25 per cent respectively. However, at these high salt concentrations the actual growth of cotton and lucerne was much restricted. The effect of salts on plant growth will, however, be discussed in Chapter 33, but here it is relevant to mention that plants do not wilt so sharply when growing in salt solutions, and the leaves keep their turgor even when very little water is being transpired and when the moisture stress is so high that all growth has ceased.

[1] *Soil Sci.*, 1947, **63**, 341.

The Available Water in Soils

Plants growing in soils of low salt content under drought conditions can dry the soil in their root zone considerably below field capacity before they begin to suffer from lack of water. Veihmeyer and his associates,[1] working mainly with irrigated orchard crops, have maintained that all the water in the root zone held at a suction less than the permanent wilting suction is readily available to the crop, and that there is no advantage in irrigating a crop until it has used up all this water. They could, therefore, define quite definitely the quantity of available water a soil can hold: it is the water held between the field capacity and the permanent wilting-point; and, in their view, it is all equally available to the crop for its growth. This concept of available water is only of value if Veihmeyer's assumption that all this water is equally available to all plants is correct: it becomes meaningless if the assumption is seriously wrong. In the first place plants have varying abilities to extract water from soil: maize and potatoes, for example, cannot take as much water as the small grains or lucerne. In the second place, the actual values for the available water obtained by Veihmeyer are subject to an uncertainty, for he determines the permanent wilting-point of the soil not when it is in its natural condition, but only after it has been dried and passed through a 2-mm. sieve. Hence, his values for available water depend on the additional assumptions that the salt content of his sample in the laboratory is the same as the soil in the field when near its wilting-point, and that the moisture content of the soil at its permanent wilting-point is independent of the actual structure of the soil—an assumption that is certainly approximately correct for many soils, but whose validity has not been critically examined for a sufficiently wide range of soil types for its limitations to be known.

Veihmeyer's assumption appears to be valid for a wide range of crops and soils in the field, and it has been extensively used to predict when irrigation is necessary, and how much water should be given at each irrigation. But it is not universally true in the field, and the conditions under which it fails are not yet clearly defined. The surprising feature, however, is that it should be of any practical value, for, as already shown in Fig. 38 for beans, and as both C. H. Davies[2] and J. L. Haynes[3] has shown for maize, when these plants are grown in controlled laboratory conditions, their growth is roughly inversely

[1] For prune and peach trees, see *Hilgardia*, 1927, **2**, 125; *Calif. Agric. Expt. Sta., Bull.* 479, 1929, and 573, 1934; for apples and pears, *Bull.* 667, 1942; for cotton, *Bull.* 668, 1942; for grapes, *Proc. Amer. Soc. Hort. Sci.*, 1931, **28**, 151; for walnuts, 1937, **35**, 289; and for growth rates of fruit on pears, peaches and prunes, 1942, **40**, 13; for sugar-beet, L. D. Doneen, *Ann. Amer. Soc. Sugar-Beet Tech.*, 1942.

[2] *Bot. Gaz.*, 1940, **101**, 791.

[3] *J. Amer. Soc. Agron.*, 1948, **40**, 385.

proportional to the suction of the water in the soil, decreasing continuously as the suction rises from about 1 atm., i.e. just drier than field capacity.

Veihmeyer's assumption will fail whenever the plant roots cannot ramify throughout the soil zone sufficiently uniformly to extract all the usable water fairly rapidly, for once the soil in the immediate neighbourhood of the plant root is in the wilting range, water can only move very slowly from moister soil through this zone. Hence the tendency for crops which make a great weight of root system, and which therefore can ramify throughout the whole soil mass, to extract more water from a soil than those which have a smaller system.[1] Again, M. R. Lewis and his co-workers,[2] studying pears in some heavy Oregon soils, and J. R. Furr and C. A. Taylor,[3] studying lemons in some heavy Californian soils, found that the trees suffered from water shortage when only one-third of the available water in the top 3 to 4 feet had been used, but they also found that in these soils the tree roots were very unevenly distributed throughout the root zone.

Veihmeyer's assumption can also fail on light soils. Thus, Furr and Taylor in California, and H. R. Oppenheimer and D. L. Elze in Palestine,[4] working with citrus—lemons, oranges and grape-fruit—on light soils found that the rate of fruit growth could be limited by lack of water before the transpiration rate was affected and whilst the moisture content of the soil in the top 3 to 4 feet was above the wilting-point under conditions when the roots were evenly distributed throughout the soil.

These failures could be due to a wrong value of the wilting-point moisture being used through the soil having a lower salt content when brought into the laboratory for the determination of its wilting-point than when it is near its wilting-point in the field. However, it is unlikely this is the sole cause of the failure, even if it is of any importance, for K. Mendel[5] found that the stomata of orange leaves close during the heat of the day, and they remain closed all day when the suction of the water in the soil has risen to 3·5 atm.

The Amount of Available Water held by a Soil

The amount of water held by a soil that is available to plants depends on the amount held per unit volume of soil and on the depth of soil from which plants can extract their water. All measurements and calculations of available water should always be made on the volume

[1] For example, see R. D. Lane and A. L. McComb, *J. Forestry*, 1948, **46**, 344.
[2] *U.S. Dept. Agric., Tech. Bull.* 432, 1934; *Plant Physiol.*, 1935, **10**, 309.
[3] *U.S. Dept. Agric., Tech. Bull.* 640, 1939.
[4] *Rehovoth Agric. Res. Stat., Bull.* 31, 1941.
[5] *Rehovoth Agric. Res. Stat., Bull.* 37, 1945.

basis; for it is only available water per unit depth of soil that is of significance for plant growth, not available water per unit weight of soil. In practice, however, one has often to measure available water on the weight basis and, if so, it is then essential to measure, and not to assume, the weight of unit volume of soil. Table 88 demonstrates how moisture contents calculated on a weight basis can give quite a different picture from those on a volume basis: the water content of this Greenville soil, which is a deep uniform loess, decreases with depth on a weight basis, but remains almost constant per unit depth of soil.

TABLE 88

The Variation of Moisture Content with Depth in a well-drained Loess Soil on a Weight and on a Volume Basis[1]

Moisture contents measured 68 days after flooding, with evaporation prevented
Fallow Soil, Greenville Farm, Logan, Utah

Depth of soil in feet	0–2	2–4	4–6	6–8
Water per 100 gm. of dry soil[2]	17·6	16·6	15·9	15·75
Density of soil particles[3]	2·695	2·745	2·755	2·755
Grams of dry soil per c.cm. of soil[3]	1·25	1·295	1·335	1·37
Pore space, per cent of total volume	53·6	52·8	51·5	50·3
Water per 100 c.cm. of soil	22·0	21·5	21·2	21·6

The amount of available water per unit volume of soil, usually measured in inches of water per foot of soil, is calculated as the difference between the volume of water held per foot at field capacity and at the permanent wilting-point. It is not very dependent on the texture of the soil, although very light soils can only hold small quantities of available water. Table 89, referring mainly to irrigated soils from the western U.S.A., shows how little the texture controls the available water present, and how a heavy soil may hold less available water than a light loam.

Available water can be increased to some extent by adding organic matter to the soil. An extreme case shows the limited amount of increase possible. On Broadbalk, at Rothamsted, one plot has received ninety-three dressings of farmyard manure at 14 tons per acre between 1843 and 1943, and its neighbour has received no manure at all during this period, and the field is ploughed to about 6 to 8 inches deep. Table 90 shows that the available water in the top 9 inches has been

[1] I am indebted to Dr. R. K. Schofield for this table.
[2] O. W. Israelsen, *Hilgardia*, 1927, **2**, 516.
[3] J. A. Widtsoe and W. W. McLaughlin, *Utah Agric. Expt. Sta., Bull.* 115, p. 201, 1912.

increased from 2·0 to 2·7 inches, or by 35 per cent, due to these ninety-three dressings of manure, but has barely been affected in the 9 to 15 inch layer. The high figure for the unmanured plot in the 15 to 21 inch layer is due to it having a higher clay content (53 per cent) than the

TABLE 89

The Field Capacity, Wilting Point and Available Water in Certain American Soils[1]

Soil	Field capacity[2] on oven-dry weight basis	Permanent wilting-point on oven-dry weight basis	Available water, inches per foot
Yuma sand	4·8	3·2	0·3
Delano sandy loam	9·1	4·2	0·8
Fresno sandy loam	11·1	3·1	1·3
Salinas fine sandy loam	28·2	20·0	1·3
Wooster silt loam	23·4	6·1	2·9
Aiken clay loam	31·1	25·7	0·7
Gila clay	30·4	16·0	2·4

TABLE 90

The Effect of Repeated Dressings of Farmyard Manure on Available Water in Broadbalk Soil[3]

Available water in the 9- or 6-in. sample in inches

Depth in inches	With farmyard manure	Unmanured	Difference
0– 9	2·68	1·97	+ 0·71
9–15	1·17	1·04	+ 0·13
15–21	1·13	1·54	− 0·41

other samples (23 to 31 per cent). Hence, this large amount of farmyard manure has not increased the available water in the top 9 inches by more than 0·7 inch, though in periods of dry springs this increase can be of great importance for shallow-rooted seedlings. American experience, with less extreme dressings of farmyard manure, indicates that a given series of dressings of farmyard manure raises the available water rather more in light than in heavy soils.[4]

[1] From J. H. MacGillivray and L. D. Doneen, *Proc. Amer. Soc. Hort. Sci.*, 1942, **40**, 483.
[2] Measured as the moisture equivalent.
[3] E. W. Russell and W. Balcerek, *J. Agric. Sci.*, 1944, **34**, 123.
[4] G. J. Bouyoucos (Michigan), *Soil Sci.*, 1939, **47**, 377; L. Havis (Ohio), *Proc. Amer. Soc. Hort. Sci.*, 1943, **42**, 497.

The depth from which plants take their water is very variable. Wheat and barley rarely take water from below 6 feet, even in the Great Plains of the U.S.A., whilst they can sometimes suffer from drought on well-drained deep soils when they are drawing water from a depth of only 3 to 4 feet. Maize probably cannot take water from quite such a depth as wheat and barley, but the sorghums can probably take it from a rather greater depth. Grasses, i.e. pastures, meadows and prairies, in general take their water from smaller depths than wheat and barley, whilst sugar-beet probably goes deeper. Some of the leguminous crops, such as sweet clover, but in particular lucerne, can go down to very considerable depths; thus, on the loess soils of Kansas and Nebraska, lucerne can dry out the subsoil to 20 to 30 feet in three to six years,[1] though its behaviour here seems exceptional.

Orchard trees on permeable, well-drained soils can certainly take water from 9 to 12 feet depth, though, as Veihmeyer[2] has shown, they can wilt and suffer from drought if the top 6 feet of soil is dried to the wilting coefficient. On heavy soils, however, they often cannot get much water below 3 feet, even in arid regions. Some authors have reported water being taken by orchard trees and vegetable crops from depths of 16 to 20 feet, but these reports are mainly from the loess soils of the Great Plains of the U.S.A.—soils which, as Israelsen and others have shown, are characterised by displaying the phenomenon of slow or delayed drainage very strongly (see p. 353), and the authors making these claims do not appear to have considered seriously this alternative explanation of their results. However, it appears that under some forest and grassland conditions, as, for example, in the hills of California, the soil may be dried down to 10 feet or more, and the water deficit may be as high as 20 inches.[3] A soil with such a deficit, if its surface is properly protected, is ideally suited to absorb the water from cloudbursts, such as sometimes occur in these hills during the winter season.

Plants take water easiest from directly underneath them, and tend to dry out the superficial layers before going deeper. In dry periods the soil in this superficial layer under the plant can be dried out to under the wilting-point, whilst the roots are taking water rapidly from soil either deeper down or farther away laterally.[4] Fig. 39,[5] taken from some results of H. H. Nicholson for the drying out of a heavy

[1] T. A. Kiesselbach, J. C. Russel and A. Anderson, *J. Amer. Soc. Agron.*, 1929, **21**, 241; 1934, **26**, 422; H. E. Myers, ibid., 1936, **28**, 106; C. O. Grandfield and W. H. Metzger, ibid., 1936, **28**, 115.

[2] *Hilgardia*, 1927, **2**, 125.

[3] M. Donnelly, *Trans. Amer. Geophys. Un.*, 1942, 544; J. W. Tourney, *U.S. Dept. Agric. Yearbook*, 1903, p. 279.

[4] M. B. Russell, F. E. Davis and R. A. Blair, *J. Amer. Soc. Agron.*, 1940, **32**, 922.

[5] I am indebted to Dr. R. K. Schofield for this figure.

soil under pasture in Cambridge during the summer, illustrates this effect. Almost the full deficit is built up in the top 10 inches before much water is removed from greater depths. This figure also shows the condition of the soil after a dry autumn and winter, when the rainfall was not sufficient to make good the deficit built up during the preceding summer.

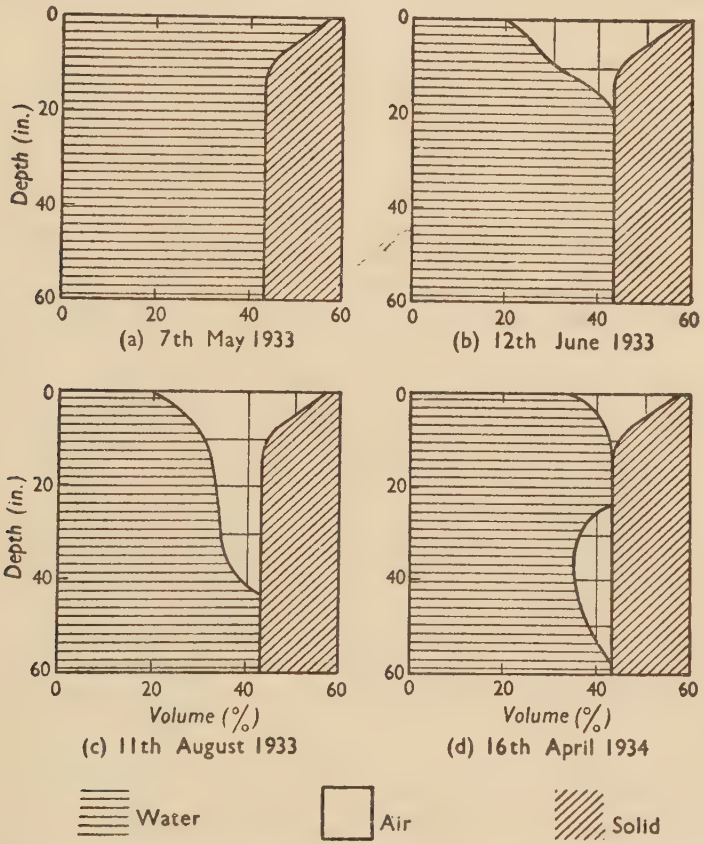


FIG. 39. The distribution with depth of water deficit in the soil during a drought. (Gault clay pasture, Cambridge University Farm.) The actual water deficits are: 7th May 0·0 in., 12th June 2·8 in., 11th August 5·0 in., 16th April 1·0+1·7=2·7 in.

There is very little difference between deep- and shallow-rooting crops in the early stages of drying out the soil, and this can be illustrated by comparing the depths from which deep-rooting lucerne and shallow-rooting citrus take their water under standard conditions of irrigation on light soils in California and Arizona, as is shown in Table 91. The correspondence between the levels from which these two crops take

TABLE 91

Depth from which Lucerne and Citrus Trees take their Water under Standard Irrigation Practice

Soil—Sandy Loam in California

Depth	Proportion of water taken from these depths	
	Lucerne	Citrus[1]
0–2 ft.	62	66
2–3 ft.	15	16
3–4 ft.	12	10
Below 4 ft.	11	8

their water under normal irrigation practice appears to be surprising when compared to the differences that they show under drought conditions. But these observations must be correctly interpreted. Lucerne can grow under conditions of severe drought, but its growth is limited. Thus, A. S. Hunter and O. J. Kelley[2] showed that the growth of lucerne is checked when the top 3 feet of soil have become dried out even when there is an abundant supply just below that depth.

Plants can use not only the water in the root zone, but also some water from the soil immediately below, and an estimate of the amount of water the deeper layers of the soil can supply can be made experimentally, for if the roots are removing water from the base of the root zone, water is moving up from the soil below in the same way as if the base of the root zone was exposed to the atmosphere and water was evaporating from it at the same rate. The change in moisture deficit in a soil during a drought can be followed with the help of a curve such as that in Fig. 40.[3] This curve shows the moisture deficit in a well-drained pasture on either the Rothamsted clay loam or the Woburn sandy loam for a given potential transpiration, that is, the transpiration that would have taken place from a similar pasture but in which the water table was sufficiently near the surface to keep the grass roots in moist soil. The curve A D shows the rate of loss of water by evaporation from the moist soils under low temperatures and slow drying rates, as explained on p. 358, and therefore represents the amount of water that can move up by capillarity into the root zone from below. The total amount of water available to the crop is therefore the amount of water

[1] Similar figures were obtained for citrus in Salt River Valley, Arizona, by K. Harris *et al.* (*Arizona Agric. Expt. Sta., Bull.* 153, 1936), who concluded from this that citrus must be irrigated as soon as the top 2 ft. of soil is dry.

[2] *Soil Sci.*, 1946, **62**, 441.

[3] H. L. Penman, *J. Soil Sci.*, 1949, **1**, 74.

present in the root zone plus that which can move up by capillarity. In Fig. 40 the straight line portion A'A represents the amount of this root-zone water, all of which is considered to be equally easily available. The figure shows that in this example, although there are only 3 inches of water in the root zone, the transpiration of the crop does not begin to be affected until after the crop has transpired 4 inches. After that, however, the soil rapidly ceases to be able to provide water for transpiration. For the next inch of potential transpiration the soil will only

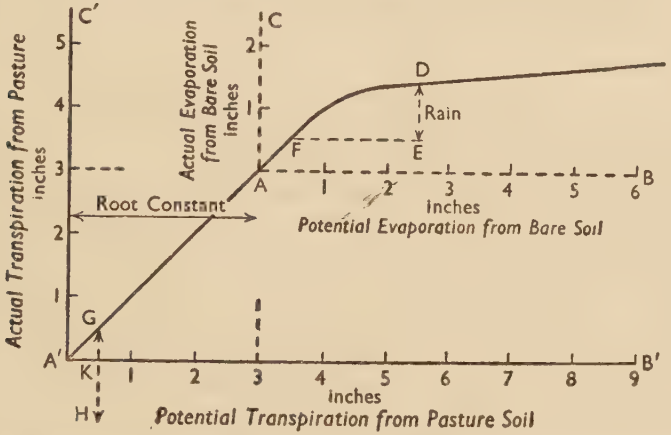


Fig. 40. The relation between the actual loss of water by transpiration from a well-drained pasture during a drought and the potential loss if there had been an adequate water supply within the root range (Rothamsted and Woburn Soils). (For explanation of the letters, see text.)

be able to provide a third of an inch, and afterwards for each inch of potential transpiration the soil can only supply about one-twelfth of an inch.

This curve, together with Penman's formula for computing the transpiration of a turgid crop from meteorological data, given on p. 368, allows one to calculate the water conditions in the soil at any time. Thus, if the soil had a water deficit represented by the point D, and rain fell equal to D E, the moisture deficit in the soil would then be represented by the point F. Similarly if it had a deficit represented by G, and a rain equal to G H fell, then a quantity of water equal to K H would have to drain out of the soil. Penman has given examples of the kind of information one can compute from this curve such as the prediction of the date at which drains under a pasture field will begin to run in the autumn.

CHAPTER XXII

THE CONTROL OF SOIL MOISTURE IN PRACTICE

Removal of Excess Water by Drainage

ARTIFICIALLY DRAINING A soil is a necessary operation under two distinct conditions: if the soil has a high water table, or if excess surface water cannot penetrate reasonably rapidly to below the root zone of the crop.

Soils having a water table sufficiently high for the capillary fringe, that is, for the soil that is kept wet by capillarity above the water table, to reach the surface always need to have their water tables reduced. The minimum allowable depth of the water table below the soil surface depends on the crop to some extent: thus fruit trees need a deeper water table than grass, for if the water table is too high their root system is too shallow to anchor them firmly against high winds when the soil is wet. It is probable that agricultural crops can only be cultivated easily in temperate regions if the water table never rises to within 24 to 30 inches of the surface, but it is usually reckoned that it should be below 3 feet, though rather higher water tables are allowable for pastures or meadows.[1]

The optimum depth of the water table, however, depends on circumstances. On peat and fen soils, which oxidise away rapidly on cultivation, it is usually considered desirable to have as high a water table as possible, for the higher the water table the slower the rate of oxidation of the peat.[2] However, English fen farmers for some reason that has not been established, do not agree with this: they like the water table to be as deep as possible. Again, if the ground-water contains enough dissolved salts to harm the root system of the crop, it should be sufficiently deep for its capillary fringe to be below the bottom of the crop's root system, and depths of less than 10 feet are considered undesirable.

The second type of soil needing draining is that in which surface water will not drain away through the soil quickly enough, with the consequence that it either stands in pools on the field, or else it fills all the main soil pores and prevents the plant roots being adequately aerated. The main principle to bear in mind when rectifying defects of

[1] For experimental results on the effect of depth of water table on crop yield, see R. Schwarz, *Kulturtech.*, 1932, **35**, 448, for canary grass; H. B. Roe, *Minnesota Agric. Expt. Sta., Bull.* 330, 1937; H. Burgevin and S. Hénin, *Ann. Agron.*, 1943, **13**, 288.

[2] For an example from the Florida Everglades, see B. S. Clayton and J. R. Neller, *Proc. Soil Sci. Soc. Flor.*, 1943, **5 A**, 118; J. R. Neller, *Soil Sci.*, 1944, **58**, 195.

drainage under these conditions is that water can only move at an appreciable rate through cracks or other discontinuities in the soil structure: it cannot move through the constitutional pores, i.e. the pores between the constituent soil particles forming the soil structure, of even light loams rapidly enough for practical purposes. Drainage can, therefore, only take place through cracks and spaces between soil crumbs in medium and heavy soils; and soils can be in need of drainage either because there are not sufficient coarse pores to let the water through the superficial layers quickly enough, or because the permeability of the deeper subsoil is too low to let the surface water drain away down to the water table. If the cause of the bad drainage is due to the water being unable to percolate through the surface layers of the soil because of insufficient coarse pores, then proper cultivation or soil management is adequate to remedy this defect. The cause of this trouble may be due either to muddy water running over the land and depositing its load of mud into the coarser pores, or to rain breaking up the surface tilth with the consequent filling up of these pores: preventing muddy water entering the area in the first case, and protecting the surface against the rain in the second, are the proper methods to be employed. If a compact subsoil is the trouble, deep cultivation, or deep ploughing to get underneath the compacted layer, is required. If the cause of the bad drainage is that the deeper subsoil is too impermeable to allow water to percolate below the root range of the crop quickly enough, then the field must be drained artificially. This is done by digging a suitable system of ditches and, if necessary, underdraining the land between them, using either a system of tile or mole drains.[1] Thus, the water falling on the surface of the soil can flow through cracks in the soil into the drains and through the ditches away from the area. If, but only if, the drainage system allows surplus subsoil water to be removed rapidly, its efficiency can often be increased by deep tillage, either ploughing or subsoiling, as this increases the number of channels the water can seep through from the surface into the drains.

The success of a drainage system depends on the stability of the soil structure, i.e. both on the length of life of the various fissures and wide pores in the soil that let the water through into the drains, and also on the clearness of the water entering the drains. Clay soils typically have a stable structure in England and troubles due to silting up of the drains and blocking up of the wide pores are unusual. Their stability may be increased by liming the soil, as the drainage water

[1] For a discussion of the principles of field drainage, see M. G. Kendall, *Practical Field Drainage* (a series of articles in *Farm Implement and Machinery Review*, 1944, **70**); H. H. Nicholson, *The Principles of Field Drainage*, Cambridge, 1942; J. L. Russell, *J. Agric. Sci.*, 1934, **24**, 544.

from unlimed clay soils may be more turbid than from limed,[1] and decreased by heavy dressings of sodium nitrate, using the same criterion of the increased turbidity of the drainage water.[2] The great difficulties in England arise with silt soils, for these have a weak, unstable structure. So much silt enters the field drains that devices such as silt traps are essential, and very careful management of the land is needed to keep the wide soil pores open, for they are rapidly filled up with muddy water unless considerable skill is used. The permeability of these soils can be maintained by proper cropping and in particular by the use of potentially deep-rooting crops such as lucerne. Such crops not only open up new channels through the soil but they also tend to stabilise the soil structure. It has not yet been established whether lucerne leys will be helpful on the silty wealden clays of South-East England where they are now being tried, but they can improve the permeability of silt loams in Iowa.[3]

Drainage improves the fertility of a medium to heavy soil for many reasons. It improves the aeration of the soil if the soil contains any appreciable volume of coarse pores that are emptied as a consequence of the draining; but it also improves the aeration of heavy soils having practically no air-space when drained, for it removes all stagnant water from the crevices and cracks in the soil, and allows oxygenated rain-water to penetrate rapidly into the subsoil. In consequence of this improved aeration of the subsoil, and removal of stagnant unoxygenated water, crops can develop a deeper root system, and this is particularly important during the winter when transpiration is low. A young plant of winter wheat can, for example, carry a well developed root system in these cracks on a heavy soil, so that as soon as the warmer weather of spring comes, it can start growing quickly as its extensive root system can tap a large volume of soil for nutrients. The corresponding plant on the undrained clay will only carry a very restricted root system, of which only a small proportion is capable of absorbing water and nutrients, as explained in Chapter 24, so it will only make very slow growth in the spring, as it will not be able to tap a sufficient volume of soil for an adequate nutrient supply. The stronger plant on the drained soil will also be able to withstand periods of rapid transpiration during a drought much better than the weaker plant on the undrained, because of its much more extensive root system at the onset of the dry period. This effect of deeper rooting and greater vigour of the crop will also allow it to dry out the soil more during the drought, hence increase the amount

[1] E. C. Childs (*J. Agric. Sci.*, 1943, **33**, 136) found 260 parts per million of silt and clay in the drainage water from an unlimed clay pasture and only 70 parts per million from an adjacent area recently limed.

[2] A. D. Hall, *Trans. Chem. Soc.*, 1904, **85**, 964.

[3] G. W. Musgrave and G. R. Free, *J. Amer. Soc. Agron.*, 1936, **28**, 727.

of cracking that occurs in the subsoil, and hence again allow water to drain through the soil more easily in the following wet weather. Thus, vigorous crops on heavy land can help create, and stabilise when created, the cracks and fissures which are essential for the downward movement of water and the improvement of the aeration.

Draining surplus water away has other desirable consequences. Drained land may warm up quicker in spring than undrained, particularly if drainage removes an appreciable proportion of the water in the soil, i.e. if the soil has an appreciable specific yield. The surface soil will warm up quicker because its specific heat is reduced by the surplus water being removed, but the same result applies to the sub-surface soil, though there appears to be very little information available on the magnitude and importance of this warming-up at depths of, say, 4 inches or 1 foot. The combined effect of improved aeration, and possibly higher temperatures, encourages microbiological decomposition of plant residues, leading eventually to an increased rate of nitrification.

Draining can have one other important effect for autumn-sown crops or for leys and grassland. The surface of a water-logged soil tends to heave, or be lifted upwards, when it becomes frozen, with the consequence that if any plants are growing in the soil they get lifted up with the surface and may have all their roots broken in the process. Heaving of soil in frosty weather is almost confined to soils containing an appreciable volume of water held in the coarser pores, hence draining a soil always reduces the liability of the surface to heave, and its magnitude if it does.

Irrigation

Irrigation consists in applying water to the land in such a way that a reasonable proportion of the root zone of the plant is moistened. The water can be applied either as a spray or artificial rain, or it can be run over the land as a sheet of water—flood irrigation—or it can be introduced into the subsoil through leaky pipes—sub-surface irrigation. Spray irrigation is preferable where only small amounts of water need be given, as, for example, by market gardeners in England; flood irrigation in one form or another is the typical method used in the irrigation projects of the arid regions; and subsurface irrigation is still in its infancy owing to the technical difficulties involved. Little detailed work has been done on the relative advantages of these methods, but, as recent work in Palestine has shown, good crops can be grown with less water if spray rather than flood irrigation is used, due to the more even distribution of water so achieved. Spray irrigation is, however, limited to areas in which soluble salts cannot accumulate in the soil

surface: it is excellent for supplementary irrigation when at another period of the year there is enough rain to wet the subsoil to well below the depth of the root zone.

The fundamental problem underlying all irrigation projects in arid regions is preventing soluble salts accumulating in the surface soil,[1] and this whole problem is discussed in more detail in Chapter 33. Soluble salts accumulate because the irrigation water itself usually contains them, and since most of the water applied is evaporated, either directly or through the plant, the salts tend to remain behind. Thus, if the irrigation water contains 100 parts per million of salt, which is a good sample of water, each acre foot transpired leaves behind nearly $2\frac{1}{2}$ cwt. of salt per acre; and much irrigation is practised with water containing 500 parts per million and 3 acre-feet may be used per year, thus salts may accumulate at the rate of about 2 tons per acre per year. They have, in consequence, to be washed away either into the subsoil below the root zone of the crop or into drainage canals and so back into the river below the area, and in either case a part of the irrigation water must be used to carry away these salts—the proportion needed for this purpose increasing with the concentration of undesirable salts in the water. C. S. Scofield,[2] for example, found that in three irrigated areas in the south-west of the U.S.A. which were supplied with water containing about 500 parts per million of salts—a fairly high concentration—one-quarter of the water applied to the land had to be used just for carrying away these salts.

The second danger is that the ground-water, which in arid districts always contains soluble salts, often derived in part from salts initially present in the superficial layers of the soil profile, may rise if too much water is applied, or if water can seep out of the canals carrying the irrigation water, and once this comes near the surface the zone of plant roots becomes very limited, and in depressions the capillary fringe may come up to the surface of the soil. Thus, salts may very rapidly accumulate in the surface at such high concentrations that successful crops can no longer be grown.

The three essential features of a successful irrigation scheme are, therefore, adequate control of the ground-water level, the ability to move soluble salts from the surface soil down below the root zone or into drainage canals, and the ability to get the water spread and absorbed evenly over the land.

Ground-water levels should never be allowed to rise higher than 6 feet below the surface and should, preferably, be below 10 feet. If this level cannot be adequately controlled by careful use of water, then either

[1] For a recent bulletin on this subject, see H. E. Hayward and O. C. Magistad, *U.S. Dept. Agric., Misc. Publ.* 607, 1946.

[2] *J. Agric. Res.*, 1940, **61**, 17.

a suitable system of drainage or interceptor ditches must be constructed to remove the water, or the ground-water must be pumped into drainage canals.

The soil must also be kept permeable both to help leach the salts down into the ground-water and also to allow the applied water to penetrate reasonably rapidly and uniformly. Slow penetration of irrigation water gives temporary water-logging, and under the high temperatures that often prevail in most irrigated regions, very short periods of water-logging may deplete the oxygen in the soil air so much that the roots are weakened sufficiently for them to be killed or attacked by root-rot fungi (see p. 215). Thus, V. A. Wager,[1] in California, found that water-logging the roots of an Avocado for one day allowed them to be attacked and killed by the fungus *Phytophthora cinnamomi*, although if the fungus was absent from the soil, water-logging for nine days did no serious harm to the tree. For relatively impermeable soils a suitable system of husbandry must be adopted as, for example, one including deep-rooting crops, such as lucerne, and the keeping of dairy cows to provide manure. A system producing farmyard manure is also often advisable on very permeable land, for the manure both decreases its high permeability and also increases its low water-holding power. In general, for all irrigation projects it is, in fact, desirable to maintain a high level of organic matter in the surface soil; hence, leys, green manuring, cover crops and farmyard manure are all desirable adjuncts of irrigation rotations.

The principles used to decide when and how much water should be applied have already been discussed; they depend on putting back into the soil the water deficit that exists in the root zone just before the crop begins to suffer from lack of water, with sufficient excess to ensure any accumulated salts are washed down into the subsoil or the drains. On many soils, as Veihmeyer and his associates have shown, this can be calculated as the number of inches of water held by 4 to 6 feet of soil between its field capacity and permanent wilting-point; but not all soils can be allowed to build up such a large deficit as this, and so need more frequent and lighter irrigations, but, in consequence of the difficulties inherent in distributing water evenly over the land by all methods of flood or furrow irrigation, they need a correspondingly greater total quantity of water.

If land is plentiful and water scarce, the most efficient way of using the water is to apply small amounts of water over large areas rather than large amounts over small. This is illustrated by some results of J. A. Widtsoe,[2] given in Table 92, for dry land farming in Utah, where using $7\frac{1}{2}$ inches of water on 4 acres gives about three times the yield

[1] *Hilgardia*, 1942, **14**, 519. [2] *Utah Agric. Expt. Sta., Bull.* 116, 1912.

of 30 inches applied to 1 acre. Naturally, if land is scarce and water plentiful, the 30 inches per acre, which gives a greater yield per acre than the $7\frac{1}{2}$ inches per acre, constitutes a more intensive and, therefore, a preferable use of the land.

The methods of applying irrigation water are fully treated in the literature and will not be discussed here; but it is important to ensure that the irrigation water does not run rapidly enough over the land to cause erosion, as not only is this directly harmful but it also makes the water muddy, and hence hinders its rapid entry into the soil.

TABLE 92

Yield of Crops for a given Quantity of Water used over Different Areas
Greenville Farm, Utah

Crop	Yield from 30 acre in. of irrigation water given over	
	1 acre	4 acres
Wheat, grain in bushels. .	47·5	166
Maize, in bushels . . .	97	317
Lucerne, hay in tons . .	3·6	14·3
Sugar-beet, roots in tons .	20·8	64·8

The quality of the water used in irrigation is of fundamental importance for the permanence of every irrigation system. All water contains salts, whose cations are mainly calcium, magnesium and sodium, and whose anions are sulphates, chlorides and bicarbonates; and, whilst high concentrations of calcium, for example, are desirable, high concentrations of sodium or chloride ions in particular, and to a less extent sulphate ions, are very undesirable.

The maximum permitted salt content of irrigation water depends on the soil. It is safe to use low-quality water on permeable soils well supplied with calcium carbonate and having a deep ground-water surface, for any excess salts in the surface can easily be leached to below the root zone. On the other hand, relatively pure water, or water very low in sodium and chloride ions, is essential on heavy soils, for then nearly all the salts in the irrigation water remain in the root zone of the plant, and if any appreciable concentration of sodium or chloride ions is allowed to build up, the soil will soon become unsuited to plant growth. This problem is, however, discussed in more detail on p. 555.

Dry Farming

Dry farming is farming under conditions of water shortage when irrigation cannot be used, and it includes the systems of agriculture in

use throughout the semi-arid regions of the world. The outstanding characteristic of most of these regions is that the limited rainfall is usually concentrated in a fairly well-marked rainy season, but the total amount of rain falling in the season, and its length, are extremely variable from year to year; and crops are often liable to almost complete loss through catastrophes, such as plagues of leaf-eating insects—e.g. locusts and chinch-bugs—violent hailstorms and complete failure of the rains. Table 93 gives a comparison of the variation in the yield of wheat from year to year in the wheat-growing areas of the Great Plains of the U.S.A. with that of the unmanured plot on Broadbalk, Rothamsted. The mean yield of wheat is about the same, but whereas yields of below 5 bushels per acre occur on the average one year in six in the dry-farming area, they only occur in one year in thirty under humid conditions, with a correspondingly far greater probability of famine occurring among populations subsisting under dry than under humid farming conditions.

TABLE 93

Variability of Wheat Yields in Semi-Arid and Humid Regions

Range	Per cent of year's yield, in bushels[1] per acre, within the following ranges							
	Failure	0–5	5–10	10–20	20–30	30–40	Over 40	Mean Yield
Great Plains[2]	4	13	18	29	23	11	2	16
Broadbalk[3] (unmanured)	—	3	24	70	3	—	—	13

The fundamental object of all systems of dry farming is to allow the crops to make the best use of the available water. This can be done in three ways: using crops that make the main part of their growth during the rainy seasons; reducing all unnecessary waste of water by run-off or weeds; and, if need be, by storing rain from one rainy season for use in the next by means of suitable fallows.

The crops normally grown between the region of mixed farming and the desert are grain crops, and they are usually only taken during the period of the year when rain is expected. Wheat and barley are the typical grains of the cooler regions and sorghums and millets of the hotter. Wheat needs a longer growing period and rather heavier soils than barley, so barley is the most suitable, and also the typical, crop grown on the edge of deserts having winter rainfall, such as those

[1] The American figures are in Winchester, and the Broadbalk in Imperial, bushels. (1 Winchester bushel = 0·97 Imperial bushel.)

[2] E. C. Chilcott, *U.S. Dept. Agric., Misc. Circ.* 81, 1927.

[3] Sixty-year mean, 1852–1911.

in North Africa and Arabia. But wheat is the preferred bread corn of the world, so it is much more widely cultivated, and is often taken in places where barley would do better.

The sorghums can withstand hot summer droughts that would shrivel up wheat and barley without coming to much harm by becoming semi-dormant, and they resume growth as soon as more rain falls. They are the typical summer cereals of the Arabian and Indian semi-deserts, and are the most reliable grain crop in the southern Great Plains of the United States; but again they are only used as human food when wheat is not available. However, they only give good yields if they can draw on an adequate supply of water during the weeks they are forming their heads. Thus Table 94[1] shows that at Dalhart, Texas, the sorghum, milo, will only produce a good crop if it can find at least 4 inches of water, in the soil or from rain, during the five weeks of heading time.

TABLE 94

Effect of Available Water at Heading Time on the Yield of Milo

Total water available from the end of July to early September	Continuous grain		Alternate grain and fallow	
	Per cent of years	Mean yield bushels per acre	Per cent of years	Mean yield bushels per acre
Under 4 in. . . .	47	10	28	10
4 in. and over . . .	53	28	72	39

Crop yields are not proportional to the rainfall or to the available water; the crop must use a considerable quantity of water before it is able to give any yield at all. In the wheat-growing areas of Kansas the first 8 to 10 inches of rain per year are only sufficient to keep the plant alive, but every inch of rain above this gives, on the average, 2 bushels of wheat per acre;[2] hence the great importance of even quite a small extra supply of water in years of deficient rainfall, as, for example, by fallowing, which supplies, on the average, an extra 3·7 inches. Extra water is even more efficient if the summer temperatures are lower than occur in Kansas; in Saskatchewan, 10 inches of water gives about 14 bushels of wheat, and every additional inch increases the yield on the average by 7 bushels per acre.[3] It is interesting to note that in some years there wheat after fallow takes over half the water it uses from the soil.[4]

[1] O. R. Mathews and B. F. Barnes, *U.S. Dept. Agric., Circ.* 564, 1940.
[2] J. S. Cole, *U.S. Dept. Agric., Tech. Bull.* 636, 1938; O. R. Mathews and L. A. Brown, *U.S. Dept. Agric., Circ.* 477, 1938.
[3] *Soil Res. Lab., Swift Current, Sask., Rept.* 1943. [4] *Canada Dept. Agric., Publ.* 595, 1938.

The period in the development of the crop at which additional rainfall, or additional water in the soil, is most beneficial depends on the crop. For sorghums in the Great Plains it is, as already shown in Table 94, around heading time; for winter wheat in the same region it is before the winter dormancy sets in,[1] the reason probably being that adequate water in this early stage encourages good germination and a well-developed root system, so that the plant is better able to withstand adverse conditions later on. Hence, the extra water retained by a fallow is available for wheat just at the period the wheat is most responsive to extra water.

The function of fallows is to store water, and they can only do this under certain definite conditions. Rain must fall during the fallow period; there must be sufficient rain to increase the soil's moisture content below 4 to 8 inches deep, otherwise it will all be lost by evaporation; the soil must be heavy enough to store a useful amount of water in its first 4 to 6 feet, but not so heavy that the plant roots cannot go down and get it, that is, it should be neither a coarse sand nor a heavy clay; and there must be no weeds. Fallows are ineffective on soils having a high water-holding power when the rain only falls in light showers, so only wetting the top 2 to 4 inches of soil. Fallows are, therefore, inefficient users of rainfall—they can rarely store more than one-quarter of the rainfall in semi-arid regions—though in Saskatchewan[2] they averaged 25 per cent over an eighteen-year period, varying from 2 to 50 per cent of the spring and summer rainfall in individual years. Fallow differs in this respect from crops: crops make full use of all the rainfall however light—a thousandth of an inch of rain falling on a crop reduces the water demands the crop is making on the soil by just this amount.

The great difficulty in managing fallows is to keep a loose, deep tilth in the surface of the soil, which is essential for weed control and for allowing the water to penetrate rapidly, without at the same time exposing it unnecessarily to the risk of being blown away by high winds. There are two distinct types of methods, which may have to be used simultaneously, for doing this: the fallow land must be divided into strips separated by strips of crop, and these strips must either run across the direction of the dangerous winds, if drifting is the sole trouble, or follow the contours if soil-washing is also troublesome; and the surface of the fallow soil must be kept protected. This can be done in two ways: the soil can be cultivated with ridging ploughs, or listers, the ridges following the contour if heavy rain is likely; or it can be cultivated with disks, duck-foot cultivators and rotary rod weeders in

[1] J. E. Pallesen and H. H. Laude, *U.S. Dept. Agric., Tech. Bull.* 871, 1941.
[2] *Soil Res. Lab., Swift Current, Sask., Rept.* 1943; *Canada Dept. Agric., Publ.* 598, 1938.

such a way that the previous year's stubble is anchored in the surface soil but sticks up from it.[1] These erosion control problems are, however, discussed in more detail in Chapter 34.

When crops are grown in regions of deficient rainfall, the yield is often very dependent on the amount of water in the soil at planting time, as was shown by F. J. Alway[2] many years ago. If there is too little water great risks are run in getting a crop. Thus, in the spring wheat area of the Great Plains in the U.S.A., J. S. Cole and O. R. Mathews[3] have shown that a good estimate of the chance of getting a profitable wheat crop can be made by finding the depth to which the soil is wet at the time of sowing, as can be seen in Table 95. If the soil is wet to a foot, or less, a profitable crop, namely, 15 bushels an acre, will only be obtained one year in six; whilst if it is wet to 2 feet it occurs once in

TABLE 95

The Effect of Soil Moisture at Sowing Time on the Yield of Spring Wheat (Great Plains, Montana to Texas)

Yield in bushels per acre

Rotation	Depth to which soil is wet at sowing time						Average
	1 ft. or less		2 ft.		3 ft. or more		
	Per cent of years	Mean yield	Per cent of years	Mean yield	Per cent of years	Mean yield	
Continuous wheat .	33	6·5	41	11·7	26	15·7	11·1
Fallow—wheat . .	5	6·9	21	12·6	74	19·9[4]	17·7

three years. The effect of fallowing is to give at least 3 feet of damp soil at sowing-time three years out of four instead of one year out of four. Tables such as these can show immediately the probability of fallowing being valuable: clearly, if the soil was wet to 3 feet at sowing-time there is no point in taking a fallow—the field should be sown; but if the soil is wet to less than 1 foot it will be very unwise to sow, and the field should be fallowed.

The effect of weeds in decreasing the efficiency of fallows can be illustrated by some results for winter wheat in Kansas.[5] This crop is

[1] For methods used in the prairie provinces of Canada, see *Canad. Dept. Agric., Bull.* 179, 1935; for the Northern and Southern Great Plains of the U.S.A., see *U.S. Dept. Agric., Farmers' Bull.* 1797, 1938, and 1771, 1937 respectively.

[2] *J. Agric. Sci.*, 1908, **2**, 333.

[3] *U.S. Dept. Agric., Circ.* 563, 1940. For the corresponding figures for milo (a grain sorghum) see O. R. Mathews and B. F. Barnes, *U.S. Dept. Agric., Circ.* 564, 1940.

[4] Soil often wet deeper than in continuous wheat.

[5] A. L. Hallsted and O. R. Mathews, *Kansas Agric. Expt. Sta., Bull.* 273, 1936. See also R. I. Throckmorton and H. E. Myers, ibid., *Bull.* 193, 1941. For the corresponding results for Nebraska, see L. I. Zook and H. E. Weakley, *Nebraska Agric. Expt. Sta., Bull.* 362, 1944.

harvested in July and the following crop is sown at the end of September, and part of the annual rainfall comes in the period between harvest and sowing. If the soil contains less than 1½ inches of available water at sowing-time, the crop is likely to be a failure, whilst if it contains more than 3 inches, a yield of over 25 bushels per acre can be expected. If the land is kept fairly free from weeds between harvest and sowing, by ploughing the land as soon after harvest as possible, in only one year out of four is the available water less than 1½ inches, and in every alternate year it has more than 3 inches. On the other hand, if the land is not ploughed until shortly before sowing, so the weeds can grow unchecked till this time, then the land has less than 1½ inches of water at sowing time every alternate year, and it has over 3 inches in only one year in eight. This benefit of early ploughing is, however, only marked in years, and in regions, when the period between harvest and seed-time coincides with a rainy season.

Yields of some crops, in particular sorghums, and possibly maize, can be increased in very dry seasons by increasing the distance between the rows of the crop, through reducing the water demands on the soil during the early part of the growing season, and thus increasing the amount of soil water available later on. Thus, in the drier parts of the western states of the U.S.A., sorghum planted in 80-inch rows will produce a yield of grain in years when those planted in 40-inch rows fail, and in certain regions the 80-inch rows only give 5 to 10 per cent less grain on the average over a run of years than the 40-inch rows.[1] It may even be profitable at times to grow sorghum or maize at 10 feet spacing between the rows, as the field may be able to store enough water to give the effect of a fallow for the succeeding wheat crop.[2]

In conditions of dry farming when water limits the yields, nitrogen fertilisers and farmyard manure are of no benefit; in fact, they may harm the crop by encouraging too much early growth. But, in good years, or particularly following fallow when there is reasonable rainfall at the critical times in the growth of the plant, yields can be increased somewhat by them. Thus, A. F. Bracken and G. Stewart,[3] working in Nephi, Utah, which has an average rainfall of 13 inches, found the yield of winter wheat after fallow could be raised by 2½ bushels per acre by dressings of 5 tons, and by 5 bushels by dressings of 10 tons of farmyard manure applied in the fallow. But on most light soils, or in areas where variations in rainfall cause large variations in yield, adding manure increases the variability of the yield, improving it in good and depressing it in poor years. This result does not apply to soils low in

[1] J. H. Martin, J. S. Cole and A. T. Semple, *U.S. Dept. Agric., Farmers' Bull.* 1764, 1936.
[2] *Kansas Agric. Expt. Sta., Bull.* 293, 1941. [3] *Utah Agric. Expt. Sta., Bull.* 222, 1930.

phosphate; unless the phosphate deficiency of these soils is corrected the crop can never begin to form a vigorous root system, hence can never make proper growth; and this may be the explanation of N. V. Kanitkar's[1] observation that 2½ tons per acre of farmyard manure may be beneficial for wheat in some of the dry-farming areas of India. However, a warning must be given that in some areas on the border of dry farming the beneficial effects of a fallow are, in fact, due to the extra nitrates the fallow has accumulated and not, as has often been considered in these areas, to the extra water.[2]

Rotations are of only limited value in really dry areas because so few crops can be profitably grown. The most important crops are grain crops, which can be used for pasture or hay instead of grain, and, under some conditions, a rotation of wheat or barley—fallow—sorghum —fallow is of value in keeping down certain insect pests such as grasshoppers.[3] Putting land down to native grasses for a few years can be of great value in weed control, and doubtless also in improving the structure of the soil by reducing its liability to blow and increasing its permeability to rain. The value of leguminous crops has not been established. Lucerne, in particular, but sweet clover to a less extent, may be harmful in regions of deficient rainfall, for they can dry out the subsoil to depths of 20 to 30 feet; and it may take several years' fallow,[4] often a very undesirable procedure because of the danger of soil blowing, to replace this water. As an example of the depth of soil dried out by lucerne, V. S. Kosinsky,[5] working in Krasnodar—a region with an annual rainfall of 500 to 700 mm.—found in August that wheat had used all the available water in the top 120 cm. of soil, one year of lucerne had used it to 140 cm., two years of lucerne to 200 cm., and three years of lucerne to 240 cm. As soon as water ceases to become strictly limiting, however, either by an increasing or more certain rainfall, or by the evaporation decreasing, mixed rotations become advantageous, as E. S. Hopkins and A. Leahey[6] have shown in detail for the prairie provinces of Canada.

[1] Dry Farming in India, *Imp. Counc. Agric. Res., Sci. Monog.* 15, 1944.

[2] See, for example, A. E. V. Richardson and H. C. Gurney, *Emp. J. Expt. Agric.*, 1933, **1**, 193, 325.

[3] R. I. Throckmorton and H. E. Myers, *Kansas Agric. Expt. Sta., Bull.* 293, 1941.

[4] For American results, see T. A. Kiesselbach, J. C. Russel and A. Anderson, *J. Amer. Soc. Agron.*, 1929, **21**, 241; 1943, **26**, 422; H. E. Myers, ibid., 1936, **28**, 106; C. O. Grandfield and W. H. Metzger, ibid., 1936, **28**, 115. For Australian results, see E. C. Powell, *Agric. Gaz. N.S.W.*, 1941, **52**, 65; F. W. Hely, *J. Aust. Inst. Agric. Sci.*, 1942, **8**, 93.

[5] *Sovet. Agron.*, 1946, No. 2, 77.

[6] *Canada Dept. Agric., Publ.* 761 (*Farm. Bull.* 124), 1944.

CHAPTER XXIII

SOIL STRUCTURE AND SOIL TILTH

Soils in their natural condition have at least some of their individual particles clustered into aggregates, or clods or crumbs; and the size distribution of these aggregates, or its converse—the size distribution of the pore spaces between them—determines the soil structure and, in part, the soil tilth.

The concept of soil tilth is still vague, and it involves at least two separate factors: the coarseness or fineness of the tilth, which is concerned with the size distribution of the aggregates; and its mellowness or rawness, properties that have been very little studied. Mellow tilths differ from raw tilths in at least two particulars: when dry, their clods are more crumbly, though they do not crumble into dust easily, and when wet they are less sticky. Hence, soils having a mellow tilth can be cultivated at both higher and lower moisture contents than soils having a raw tilth.

The importance of tilth for plant growth or for ease of managing land is still in doubt, for crop development does not seem to be anything like as sensitive to quite wide variations in the tilth as many farmers firmly believe.[1] From the field point of view the following properties of a good tilth are of great importance:

(*a*) There should be a continuous system of wide pores from the soil surface down to the water table or the land drains through which surplus water can move rapidly and which will allow rapid diffusion of carbon dioxide from the subsoil to the atmosphere.

(*b*) These pores should be sufficiently stable to last several years before being filled up.

(*c*) There should be volumes in between these pores that hold as much water as possible against drainage, but which are readily accessible to the plant roots.

(*d*) The surface soil should be crumbly, and the crumbs should be large enough not to blow away, but small enough to allow good germination of the seed, and sufficiently unsticky when moist for them to keep their individuality when tractors or implements move over them.

A soil can fulfil these conditions without its subsoil possessing any structure in the usual sense of the word; yet in general, on the medium to heavy soils, subsoils only possess these properties if on drying they break down easily to definite clods which are separated from their

[1] For an example of the apparent insensitivity of malting barley to the tilth of the seed-bed in England, see E. W. Russell, *Proc. Inst. Brit. Agric. Engnr.*, 1945, **3**, 99.

neighbours by fairly long-lived cracks or planes of weakness. These cracks open as the soil dries and form drainage channels down which water can seep fairly rapidly. Plate XVII illustrates this for the Rothamsted subsoil—a clay loam having a good natural subsoil structure. A cultivated surface soil usually possesses a crumb or clod structure, that is, the individual silt and clay particles, and usually the sand and gravel particles as well, are aggregated into definite clods that may range from blocks a foot or more across down to dusty crumbs a fraction of a millimeter in size.

The most desirable size for the surface crumbs or clods to have from the point of view of plant growth lies in the range 1–5 mm.,[1] rather towards the smaller limit in dry conditions and the larger in moist. Crumbs smaller than 0.5 mm. merely block the coarser pores down which water can drain and through which air enters the subsoil, without adding to the water-holding power of the soil, whilst crumbs larger than 5 to 6 mm. usually have too large an air space around them for the rootlets of seedlings.

With crumbs of optimum size Kvasnikov showed that cereals made better and earlier growth, gave higher yields and higher values of the grain-straw ratio, and made a more efficient use of the limited water supply than when the crumbs were either larger or smaller. These conclusions have been confirmed by Yoder, using cotton as the test crop.

A desirable structure, or tilth, once obtained should be as stable as possible. A tilth, or a system of wide pores, can break up in the following ways: the cements holding the particles together can be so weak that the dry crumbs can be easily broken down to dust by cultivation implements, by animals walking over the land, by the wind being able to raise dust storms that can shatter them, and by heavy rain being able to smash them. Or the cements can fail to hold the particles together when wet. This happens in some alkali soils when the surface crumbs fall down to a mud which fills up all the surface cracks, and when the subsoil clods swell and the surfaces of adjacent clods stick together and disappear. But dry clods can break up during wetting for other reasons. In the first place, the clod swells on wetting, and in the process outside bits of the clod often flake off. In the second place, adsorbed air is displaced from the dry internal surfaces of a clod on wetting, and this air has to force space for itself to occupy, and in doing so, disrupts the clod. Both these processes may cause the wider drainage pores to become blocked.

[1] A. G. Doyarenko, *Russian J. Agric. Sci.*, 1924, **1**, 451, for podsolised soils near Moscow, and V. U. Kvasnikov, ibid., 1928, **5**, 459, for semi-arid soils near Samara. See M. Krause, *Landw. Jahrb.*, 1931, **73**, 603, for a German summary of this work. See also R. E. Yoder, *Proc. Soil Sci. Soc. Amer.*, 1938, **2**, 21, and H. Dittrich, *Bodenk. PflErnähr.*, 1939, **16**, 16, for similar results.

The problems of maintaining a stable soil structure usually only concern the surface soil, for the subsoil structure is not usually subject to mechanical shattering, although a tractor wheel running on the top of a wet subsoil can destroy its natural structure and hence its permeability very effectively. The structural units of the subsoil are thus mainly subjected to the general tensions and compressions set up as the subsoil is dried or wetted, with the result that the structural units and the spaces between them possess considerable permanence. This permanence can be vividly seen in horizons in which manganese dioxide has been deposited: natural blocks of the soil look black, and, when broken naturally, break into smaller black blocks; but this blackness can easily be seen to be only a very thin film coating the soil crumbs. Very difficult problems arise when the subsoil clods are not stable to a drying and wetting cycle, for example, when the outer surface of the clods flake off on wetting, and such soils are most troublesome to keep well drained. Some of the English silt soils have this very undesirable property.

The properties of the soil structure that have been most commonly picked out for its classification are the size and shape of the structural units[1] and their stability to wetting; but, as has become obvious from the foregoing discussion, a classification can equally well be based on the geometry and stability of the larger pore spaces and cracks in the soil.[2] This is in fact probably the most profitable approach for many silt and clay soils. Pigulevsky, for example, has classified the structure of such soils by the size of the clods between the major cracks, and F. Hardy and L. F. Derraugh[3] have tried to classify the different types of cracks that develop. These latter authors have pointed out the very important role these cracks play in the general economy of impermeable clay soils: they serve as drains and allow the subsoil to remain reasonably well aerated even when the surface soil is water-logged; they form the spaces in which the plant roots and rootlets live and grow; they allow crumbly and fertile surface soil to be transferred to the subsoil; and when the soil at a suitable moisture content is ploughed or cultivated, they form the planes of weakness which allow the large clods to break down into a fine cloddy tilth. All these effects are of great importance for impermeable clays in tropical climates having a wet and a dry season and in arid areas under irrigation, such as the Gezirah in the Sudan, and parts of the Nile Valley in Egypt.

[1] For a recent discussion of some present-day systems, see G. R. Clarke, *The Study of the Soil in the Field*, 3rd ed., Oxford, 1941.

[2] M. C. Pigulevsky, *Trans. 2nd Intern. Congr. Soil Sci.*, Leningrad-Moscow, 1932, **1**, 82; *Theory, Construction and Manufacture of Agricultural Machines, Part II*, 1936, Moscow. For a summary of his methods, see E. W. Russell, *Imp. Bur. Soil Sci., Tech. Comm.* 37, 1938. C. L. W. Swanson, *Iowa St. Coll. J. Sci.*, 1941, **16**, 137, and with J. B. Peterson, *Soil Sci.*, 1942, **53**, 173, has also developed a similar method.

[3] *Trop. Agric. Trin.*, 1947, **24**, 76.

Great difficulties arise in the classification of soil structure, because both the structural units which compose the soil in the field, and the pores in the soil, have a wide range of size and shape, and there is rarely any particular property of the shapes that is sufficiently characteristic for accurate description. There is not yet any generally accepted terminology for the different shapes met with,[1] but one recently summarised by C. C. Nikiforoff[2] illustrates the kind of division that can be attempted. He recognises the following four type-shapes of structural units:

Plate-like, in which the natural cracking is mainly horizontal. This is often well developed in the A_2 horizon of leached soils or in soils rich in kaolinite.

Prismatic, in which vertical cracking is better displayed than horizontal, resulting in structural units two to five times as long as they are broad. This develops in the B horizon of many heavy soils, especially in semi-arid regions. Two types of prismatic aggregates are illustrated in Plates XIX and XX.

Blocky, in which vertical and horizontal cracking are equally strongly developed so the structural units have roughly equal axes. Their shape is, however, irregular, but like the prismatic structural units, their edges are sharp and their faces smooth. Typically, they range in size from 1 mm. to 5 cm., and Plate XVIII gives two examples of a blocky soil structure.

Granular, which differs from blocky in not having sharp edges or smooth faces, and which is in consequence more rounded. Their typical size lies in the range 1 mm. to 1 cm. and they are found in the surface layer of pasture, chernozem, and other soils high in organic matter. The granular structure also differs from the blocky and prismatic in that, when the soil is wet, there are considerable volumes of air or water between granular units, but only very small volumes between prismatic or blocky.

The actual shape of the structural units often lies intermediate between two or more of these type-shapes, but Nikiforoff suggests that they can be described by the nearest type-shapes to which they approximate, by their size and by how well the typical shape has been developed, for a well-developed structure has units that are relatively strong individually but weakly bound to their neighbours.

The pore size distribution can easily be measured in many soils by determining first the moisture-content-suction curves for the soil,[3]

[1] For some of these, see E. W. Russell, *Imp. Bur. Soil Sci., Tech. Comm.* 37, 1938.

[2] *Soil Sci.*, 1941, **52**, 193. For an earlier Russian classification, see S. A. Zakharov, *Achievements of Russian Science in Morphology of Soils*, Acad. Sciences, Leningrad, 1927.

[3] For examples of this method, see F. Sekara, *Bodenk. PflErnähr.*, 1938, **6**, 259, 288; E. C. Childs, *Soil Sci.*, 1940, **50**, 239; 1942, **53**, 79; V. C. Jamison, *J. Amer. Soc. Agron.*, 1942, **34**, 307, 393; M. B. Russell, *Proc. Soil Sci. Soc. Amer.*, 1942, **6**, 108; C. L. Feng and G. M. Browning, *Proc. Soil Sci. Soc. Amer.*, 1947, **11**, 67.

Profile of the Rothamsted Clay-with-flints soil (0–4½ft.). Note the characteristic rectangular cracking in the subsurface soil and the flat inclined surfaces in the subsoil

(*p. 398*)

Fine prismatic soil structure (natural size)
(*p. 400*)

Rounded and flat tops of prismatic aggregates (half natural size)
(*p. 400*)

which gives the volume of water in pores smaller than the pore diameter corresponding to each suction, and then plotting the slope of this curve against the suction, which gives the frequency distribution of the sizes of pore present. An example of this is given in Fig. 41 for a sample of Gault clay that was initially in crumbs between 1 and 2 mm. in size.[1] Techniques have also been developed for obtaining the size distribution and the volume of the larger pores by direct measurement using a low-power microscope.[2]

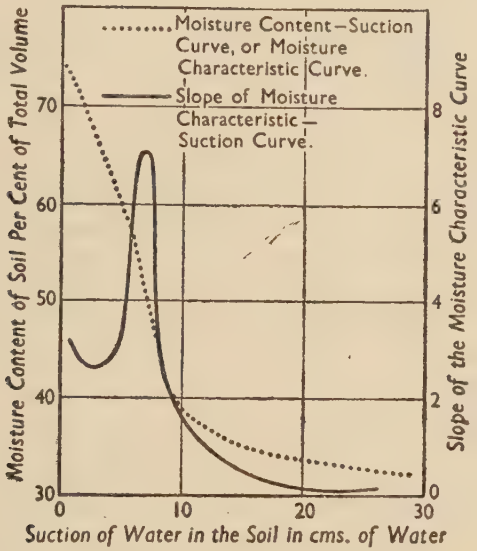


FIG. 41. The moisture content-suction curve, and its differential, for a Gault clay. (Soil initially in crumbs 1–2 mm. size.)

The water stability of the coarse pores can be easily determined by taking these crumbs through several wetting and drying cycles, and constructing slope-suction curves for the sample after each cycle. Fig. 42 shows the stability of the coarse pores in an Upper Lias clay at different depths below the surface when taken through three such wetting and drying cycles.[3] In this soil, the stability of the coarse pores obviously decreases rapidly with depth. Childs has used this method to pick out soils whose subsoil structure is too unstable for mole drainage to be a practicable method of under-drainage.

The main structural elements present in the field often have a definite structure of their own, particularly in loam and clay soils. Large clods

[1] Taken from E. C. Childs, *Soil Sci.*, 1940, **50**, 246.

[2] W. Kubiena, *Micropedology*, Ames, 1938; *Entwicklungslehre des Bodens*, Vienna, 1948; G. W. Volk and H. J. Harper, *Soil Sci.*, 1939, **48**, 141; G. C. Redlich, *Soil Sci.*, 1940, **50**, 3.

[3] Taken from E. C. Childs, *Soil Sci.*, 1942, **53**, 84.

are normally built out of smaller clods, as can be seen by dropping a dry clod on a hard floor when it will break up into smaller clods, usually of characteristic shape; and these in turn are often formed out of still smaller granules binding the sand particles together. This can be seen visually by examining the crumb under a low-power microscope, or by scratching its surface with a sharp needle, or by putting a dry crumb in water, all of which will display these granules if they have a definite existence. Crumbs that are built out of such granules

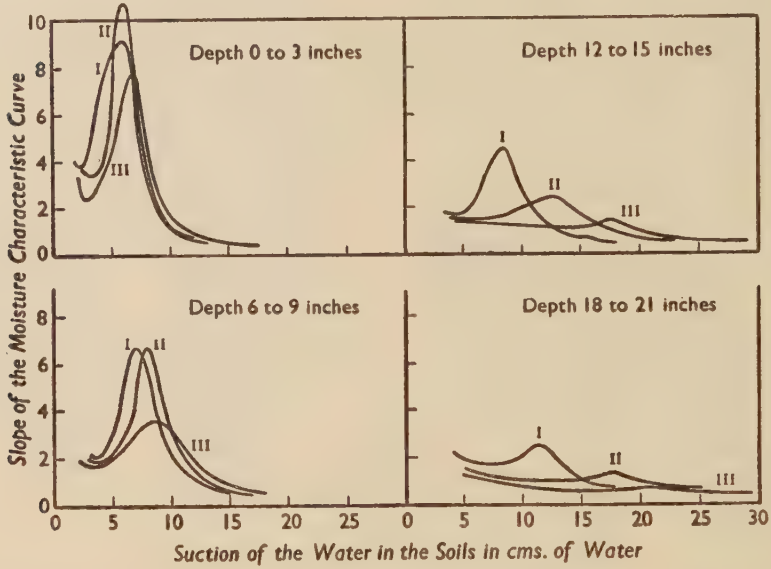


Fig. 42. The variation in the stability of the pore space distribution down the profile of an Upper Lias clay. Curve I is for the first, curve II for the second, and curve III for the third wetting. (Soil initially in crumb 1–2 mm. size.)

are said to have a well-developed micro-structure, and the granules themselves are called the elements of the micro-structure. This concept of the micro-structure of crumbs and clods is very useful, although these micro-structural elements probably have not sufficient persistence and discreteness to be properly regarded as the ultimate basic building units of the crumb structure.

Soils differ greatly in the extent to which their crumbs and clods possess pronounced micro-structure or granularity. Clay soils, particularly when low in organic matter, are liable to dry out into large hard uniform clods, and this tendency is encouraged by working or moulding the clay when it is too wet, or by replacing a proportion of the exchangeable cations by sodium when the concentration of salts in the soil solution is low. Adding calcium carbonate or soluble salts to the clay,

by increasing its degree of flocculation, increases the granularity of the clods; but unless the salt content is high, the smallest structural units into which the clods will break down will be several millimetres in size. On the other hand, soils under old pasture are aggregated into crumbs displaying a very pronounced micro-structure, and the granules composing it may be under 0·1 mm. in size.

Direct microscopic examination of crumbs or of thin sections of crumbs usually shows the main cement, or fabric, which holds the particles together. W. Kubiena[1] has given illustrations and has named the main types of cementation between particles, and the arrangements of the different types of particle in crumbs and granules. In the English and other arable soils the author has examined, however, the typical arrangement is for small clusters of particles, which cannot be properly resolved by a low-power microscope, to lie in the spaces between fairly clean sand grains. These clusters presumably hold the sand grains together the more strongly the more they fill the pore space between the sand particles.

The main quantitative methods of structural analysis in use depend on measuring the stability of the structural units to wetting either by determining their size distribution in water, as, for example, by sieving the soil on a bank of sieves in water, or by determining the rate water can percolate into the soil and its decrease with time. The first method, which was introduced by A. T. Tiulin,[2] gives results that are very dependent on the exact technique used, particularly on the dryness of the soil before wetting and on the rate of wetting, due principally to the rate at which water displaces the air from the surface of the soil particles. Thus, a moist soil, or a dry soil wetted under vacuum, breaks up less than a dry soil wetted slowly by capillarity from below, and this in turn breaks up less than a dry soil plunged into water.[3]

The stability of the structure can also be measured by determining the rate at which water penetrates into a soil, or its infiltration rate. The infiltration rate for a soil with a stable structure remains nearly constant with time, except in so far as air bubbles displaced from the dry soil particles block up the coarse pores,[4] but it falls fairly rapidly with time if the structure is unstable so the coarse pores become narrower. The principal soil types in which the wider subsoil pores are unstable to water are some silt and most alkali soils—the cause of instability in the former being that the structural units in these soils are only weak and silt particles are always flaking off the crumbs, so

[1] *Soil Res.*, 1935, **4**, 380; *Bodenk. PflErnähr.*, 1936, **2**, 1. See also his book, *Micropedology*, Ames, 1938.

[2] *Perm. Agric. Expt. Sta., Dept. Agric. Chem.*, 1928, **2**, 77.

[3] E. W. Russell and R. V. Tamhane, *J. Agric. Sci.*, 1940, **30**, 210.

[4] J. E. Christiansen, *Soil Sci.*, 1944, **58**, 355; A. F. Pillsbury and D. Appleman, ibid., 1945, **59**, 115; R. M. Smith and D. R. Browning, ibid., 1946, **62**, 243.

blocking up the pores. In practice the principal cause of a reduction in infiltration rate is not the rate at which the subsoil pores block up, either by the subsoil structure swelling or breaking up, but by the surface structure breaking down and sealing the main drainage channels. No soil structure can be made so stable in farm practice that the bare soil surface can stand up to a heavy rain storm. Once the clods are wet, heavy rain will soon break some up, and the water will become muddy and seal the surface pores. Hence, no bare soil structure can have adequate stability to withstand downpours: the surface must be protected from fast-falling raindrops either by vegetation or by a mulch of straw, manure or compost, for then the percolating water will remain clear, and the pores open, much longer.

The Breakdown of Soil Structure

The soil structure can break down in the field for several reasons. The least important normally is the breakdown of dry crumbs, which can occur if the soil particles are only loosely held together in the clods and if high winds can move an appreciable number of sand grains. Blowing sand grains can break down the surface structure, but they can only be produced in sufficient quantity to be of importance on soils having a high percentage of suitably sized fine sand particles (p. 569).

Disintegration of soil structure only occurs under natural conditions during the process of wetting, though in agricultural practice it can also be brought about by wrongly timed cultivation operations. There are two types of natural breakdown, in one of which the clay and organic matter cease to bind the particles together, and in the other of which they continue to do so.

The first type of instability, when the clay particles cease to bind when wet, has only been recognised in the field with soils having a large proportion of sodium among their exchangeable ions, although a high proportion of exchangeable potassium, or even magnesium, might give the same phenomenon. The cause of the instability is that the clay particles deflocculate on wetting, that is, there is a force of repulsion instead of attraction between them when wet, and this can easily be demonstrated by gently shaking the soil up with water, when the clay will form a stable suspension. The methods for overcoming this trouble, which of itself prevents any agriculture being practised, are discussed in Chapter 33. There are two principal types of method, one of which is always applicable as it consists in replacing the exchangeable sodium by calcium as far as possible, and the other, only useful in irrigated regions having virtually no rainfall, consists in building up a sufficiently high salt content in the soil by using slightly saline irrigation water, so

that the soil solution is always sufficiently concentrated to prevent the clay particles deflocculating.

Dry clods also break up to some extent on wetting for a quite different reason. All clods swell on wetting, some only a little, but some a great deal, and the process of swelling mechanically breaks off pieces from the clod. These pieces may be small micro-aggregates or they may represent appreciable pieces of the original clod. The larger the clod, the greater the amount of break-up due to this cause, because the greater the movement of the outer layers on wetting. This break-up is increased by a second factor, for on wetting a dry clod the adsorbed air is displaced, and in general it is displaced faster than it can diffuse into the atmosphere. Hence, wetting involves a rapid swelling due to this cause also, which is greater the more rapid the displacement of the adsorbed air, that is, the more rapid the wetting. It is an effect of little importance in coarse, sandy soils, or in dry soils wetted very slowly, as, for example, by long-continued gentle rain; but it is much more important than the mere swelling effect for loams and clays when wetted rapidly, as, for example, with flood irrigation.

Clods can also be broken down by mishandling when wet, for pressing wet clods together makes them lose their identity and become a larger plastic mass. This can happen in the field by ploughing or cultivating a soil when it is too wet, or by running a tractor or even farm stock over the land. Puddling the soil is an extreme example of this effect.

Heavy rain can also break up wet soil clods by the mechanical beating the clods receive as they stop large, fast-falling raindrops. This is the primary cause of soil erosion in most parts of the world, and, as will be discussed in Chapter 34, the only way one can prevent this happening is to ensure the raindrops hit something else, such as a vegetable mulch lying on the surface or the leaves of growing plants above the surface, provided the water can then run down gently into the soil.

The general effect of cultivating a soil is to break up the soil structure, for most cultivation operations, particularly those such as hoeing in dry weather to kill weeds, pulverise the soil and make it more dusty. But cultivations also increase the rate of oxidation of soil organic matter, some fractions of which act as cements binding the soil particles together into crumbs.

The Building up of Soil Structure in the Field

No agricultural system can be permanent that does not maintain an adequate soil structure, and failure to maintain it has been an

outstanding characteristic of some unsuccessful farming systems. The methods available for controlling the structure fall into four groups: the proper use of cultivation implements, of climate, of manures, and of growing crops; and structural control must be able to increase as well as decrease the size of the structural units.

THE EFFECTS OF CULTIVATION IMPLEMENTS AND WEATHER

The size of the clods present in a field soil can be altered by the proper use of cultivation implements and by the weather; and the alterations that can be brought about include decreasing and increasing the size of the clods and their stability.

The ability to build up larger from smaller aggregates is of most importance in sandy soils, for crumbs of medium and heavy soils aggregate together naturally on wetting and drying. The principle underlying the method for building up a good stable structure is that the optimum structure is produced when the soil is worked at the minimum moisture content that allows the soil particles to slip over one another and come into closest packing. If the soil is only worked with small pressures, the optimum moisture content for working is about the sticky point, that is, when the soil pores are just full of water, and the stability of the clods so formed falls off fairly rapidly as the moisture content differs from this optimum.[1] As the pressure of working increases, so the optimum moisture content decreases,[2] and the range of moisture contents giving a structure almost as good as the optimum increases.

The breaking down of large clods into smaller ones is easy for light soils, as the dry or nearly dry clods are easily shattered mechanically. Reducing the size of clods of medium to heavy soils, on the other hand, can be a much more difficult process requiring the proper use of weather and machinery, for cutting up wet clods or smashing dry ones —which incidentally produces much dust—requires an extravagant use of power and gives an unsatisfactory tilth.

The art of breaking up large clods of a heavy soil depends on letting the dry clods wet a little before working them. Wetting a large, dry clod has two effects, the relative importance of which depends on the method of wetting: slow wetting, such as that caused by a prolonged drizzle, encourages the clod to break into a number of smaller clods, or at least to develop internal planes of weakness allowing it to be

[1] D. G. Vilensky and V. N. Germanova, *Pedology*, 1934, p. 34; *Trans. 1st Comm. Int. Soc. Soil Sci.*, Versailles, 1934, 17. See also D. G. Vilensky, *Aggregation of Soils*, Acad. Sci. U.S.S.R., 1945. For further examples of this effect, see W. T. McGeorge, *Arizona Agric. Expt. Sta., Tech. Bull.* 67, 1937; T. F. Buehrer and M. S. Rose, ibid., *Tech. Bull.* 100, 1943.
[2] S. Hénin, *Ann. Agron.*, 1936, **6**, 455.

easily broken up by a cultivation implement; whilst rapid wetting, particularly when caused by heavy rain, encourages very small crumbs to flake off the surface of the clod. This flaking off of fine crumbs from a large clod, however, may not result in a finer tilth because if too large a proportion of these fine crumbs have been produced, they will tend to dry into another hard clod, for crumbs of many loam and clay soils finer than a half to a quarter of a millimetre cohere together when wet, particularly if some muddy water is present, and will then dry out into a coherent mass.

A second method of breaking down large clods of a heavy soil is through the action of frost on the wet clod. The effect of frost on a soil depends on its moisture content, the rate of freezing, and the amount of water left unfrozen. Slow freezing tends to cause much of the ice to be formed in relatively thick layers[1] and if the moisture content is not too high, considerable volumes of soil will be left almost ice-free and be subjected to the high pressures due to the expansion of the water on freezing. If these soil volumes have a fairly high content of unfrozen water, that is, if they have a fairly high moisture content at *p*F values around 4·5 to 5 on the drying curve, so they are relatively plastic in this condition, this pressure will give crumbs of great stability and of a desirable size[2]—between about 30 mm. and 3 mm. for the Rothamsted soil. These crumbs have a smaller pore space than the original clod, owing to the pressure they have been subjected to, so that when the soil is thawed some of the water held by the soil before the frost becomes free water and drains away. Hence, the effect of slowly freezing and then thawing wet clods of a heavy soil is to leave it rather drier than it was before the frost and with a very stable crumb structure of a desirable size distribution.[3]

This desirable frost tilth is only produced under the two conditions of fairly slow freezing of wet clods[4] and reasonable sized volumes of soil with a moderately high content of unfrozen water between the ice films. Freezing sandy soils tends to destroy the structure, for the pockets of soil between the ice films are too dry to benefit from the pressures set up by freezing. Rapid freezing of heavy soils, or freezing them when wet or at very low temperatures, encourages a more uniform distribution of ice throughout the clod, giving smaller volumes of drier soil between the ice films, which, when thawed, fall down to much too fine a tilth.

[1] For the results of Swedish experiments bearing out this point, see S. Eriksson, *LantbrHögsk. Ann.*, 1941, **9**, 80.

[2] G. Torstensson and S. Eriksson, *Kgl. Lantbr. Akad. Tidskr.*, 1942, **81**, 127.

[3] Recently C. S. Slater and H. Hopp (*J. Agric. Res.*, 1949, **78**, 341, 347), have claimed that freezing heavy soils always reduces the water stability of clay clods. The cause of this discrepancy with normal experience was not investigated.

[4] E. Jung, *Ztschr. Pflanz. Düng.*, 1931, A **19**, 326.

MODIFYING THE COMPOSITION OF THE SOIL

It has long been known that the structure or tilth of a soil can be modified by adding suitable improvers to it, or growing suitable crops on it. Claying or marling light soils, which has been practised for many centuries in parts of England, helps to bind the sand grains together and improve the water-holding power of the soil. Chalking heavy soils, applying dressings of farmyard manure or composts, ploughing in green manures, and laying land down to long leys or pastures, are all methods used by farmers for improving the tilth of their land.

The way in which lime or chalk added to a soil improves its tilth is not yet understood, for laboratory measurements have not, on the whole, shown up the benefits that practical farmers have always attributed to dressings of chalk. In any discussion on this subject two operative factors must be separated: the effect of replacing the exchangeable aluminium on the exchange complex by exchangeable calcium, and the effect of free calcium carbonate; and these factors may affect the ease with which large clods break down into smaller ones, the water stability of the smaller ones, the mellowness—or lack of stickiness when wet—of the clods, and the type of decomposition suffered by the organic matter in the soil and, in consequence, the types of organic cements being produced. Unfortunately only a few of these effects have been properly investigated.

The great weight of experimental evidence confirms the result that the stability of the crumb structure of an acid soil is not affected by increasing the amount of calcium in the exchange complex,[1] and it is possible that the exceptions to this rule[2] are due to secondary effects, as, for example, on the soil population. The effect of excess calcium carbonate again has not been rigorously established. Its effect seems to be to reduce the size of the clods in a soil[3]—a desirable effect in clays, but undesirable in sands—and at the same time it appears to increase the stability of the clods, for E. C. Childs[4] has noticed that drainage water coming from limed land had fewer suspended silt and clay particles than from unlimed. Chalking a heavy soil may increase the mellowness of its tilth, making it easier to work. This almost certainly happens on some soils, such as the Rothamsted clay, but it is hard to believe this is a general result, because some of the most difficult English clays to work, such as those on the Gault, may have a high calcium carbonate content.

[1] See, for example, L. D. Baver, *Amer. Soil Survey Assoc.*, 1936, **17**, 28; H. E. Myers, *Soil Sci.*, 1937, **44**, 331.
[2] For an example, see H. T. Rogers, *J. Amer. Soc. Agron.*, 1939, **31**, 915.
[3] For an example of this on a sandy soil, see A. Demolon and S. Hénin, *Soil Res.*, 1932, **3**, 1.
[4] *J. Agric. Sci.*, 1943, **33**, 136.

Adding fertilisers to a bare, uncultivated soil usually reduces the stability of the structure, calcium fertilisers, such as calcium nitrate, having least effect, and sodium fertilisers, such as sodium nitrate, being most harmful, with ammonium fertilisers intermediate.[1] On cropped land, however, these effects are much less striking.[2] On the clay loam soil on Broadbalk, fifty-five annual dressings of 550 lb. of nitrate of soda per acre have had no effect whatever on the structure, though both sodium nitrate and potassium chloride have harmed the structure somewhat on the heavier, less well-drained Barnfield, in continuous mangolds.

The role of organic matter in soil structure depends on the type of organic matter present. Mere organic remains, such as some types of peat, have no effect on soil structure itself—although they may assist the aeration or the water-holding power of the soil—nor is the effect of old stable humic colloidal material very great. Thus, very well-rotted composts have less effect on soil aggregation than less well-rotted ones;[3] and some fen soils, very high in organic matter, can be very poorly aggregated when dry. R. Bradfield[4] also has noted that some prairie soils when badly farmed after being broken up, can have a higher organic matter content, but a much poorer aggregation, than well-farmed neighbouring soils that have been longer in cultivation.

Dressings of farmyard manure or compost, particularly if generous dressings are given regularly, can have very beneficial effects on the soil structure. They cause an increase in the cohesion between sand particles, thus increasing the resistance of the soil surface to wind blowing and to sealing by rain storms, and they also cause an increase in the number of centres around which contraction takes place when a clay is dried. This increases the number of fine cracks that develop as a clod dries, making it more crumbly[5] and perhaps for the same reason also, less sticky.

The effect of long-continued dressings of farmyard manure on the water stability of crumbs can be illustrated on the permanent wheat and mangold fields at Rothamsted, and on other long-term rotation experiments that have been carried out in other parts of the world. At Rothamsted the proportion of water-stable crumbs larger than 0·5 mm. in the soil was increased from 28 to 55 per cent on the permanent wheat field, and from 54 to 70 per cent on the heavier soil of the permanent mangold field as the result of long-continued annual applications of 14 tons per acre of manure. This result has not,

[1] For an example, see A. Demolon and S. Hénin, *Soil Res.*, 1932, **3**, 1.
[2] For recent examples, see D. G. Aldrich *et al.*, *Soil Sci.*, 1945, **59**, 299; R. B. Alderfer, ibid. 1946, **62**, 151.
[3] J. P. Martin, *Proc. Soil Sci. Soc. Amer.*, 1943, **7**, 218.
[4] *Amer. Soil Survey Assoc.*, 1936, **17**, 31.
[5] See, for example, P. V. Vershinin, *Pedology*, 1938, 1278, for some quantitative measurements.

however, been found in all such experiments; thus twenty-eight annual dressings of 16 tons of manure to a loam soil in south-eastern Ohio[1] had little effect on the structure. Very little information is available on the effect of customary dressings of, say, 10 tons of manure once in every four to five years on the tilth; but in the few cases where experiments have been made the effect has been small or negligible.

Soil tilth can sometimes be improved by ploughing in a green catch crop, and indeed F. Y. Geltser,[2] working in Turkestan, and J. J. Kanivitza,[3] in the Ukraine, both claim that ploughing in a green crop is a more efficient way of improving the soil tilth than ploughing in farmyard manure. J. P. Martin and B. A. Craggs[4] have confirmed this result in some recent laboratory experiments, and have also found this to be the typical behaviour of these two types of material decomposing at soil temperatures in the range 10° to 25°C., but that at higher temperatures the opposite result was more typical. However, experience elsewhere has not always borne out the value of green manuring as a tilth improver, possibly because insufficient green matter has been added to effect any appreciable improvement, and possibly because, as in the tropics where green manuring may actually do harm,[5] the soil temperatures are too high to give anything but a very ephemeral improvement.

The improvement of structure brought about by additions of organic matter depends, at least in part, on the speed with which it decomposes.[6] The improvement in structure normally increases with the ease of decomposition of the material, but it mainly occurs after the first flush of decomposition is over.[7] After the maximum improvement in structure has been reached, which may only take one to three weeks if readily decomposable material is added, it may be maintained for several months with little deterioration, though in some cases, for reasons not understood, it may be much shorter-lived. The role of lime in improving soil structure on acid soils may largely lie in its power of increasing the speed of decomposition, for it appears to be more effective as a structure improver on these soils when used in conjunction with farmyard manure or other decomposable organic matter.[8]

[1] L. Havis, *Ohio Agric. Expt. Sta., Bull.* 640, 1943.
[2] *Trans. 1st Comm. Int. Soc. Soil Sci., Soviet Sect.*, 1934, A2, 73.
[3] Quoted by N. A. Sokolovsky, *Trans. 1st Comm. Int. Soc. Soil Sci.*, Versailles, 1934, 89.
[4] *J. Amer. Soc. Agron.*, 1946, **38**, 332.
[5] W. S. Martin, *E. Afric. Agric. J.*, 1944, **9**, 189. See also J. B. Peterson, *Soil Sci.*, 1943, **55**, 289, for what appears to be another example.
[6] T. C. Peele and O. W. Beale, *Proc. Soil Sci. Soc. Amer.*, 1944, **8**, 254; G. M. Browning and F. M. Milam, *Soil Sci.*, 1944, **57**, 91.
[7] J. R. McHenry and M. B. Russell, *Soil Sci.*, 1944, **57**, 351.
[8] See, for example, A. T. Tiulin and E. V. Biriukova, *Khim. Sotsial. Zemled.*, 1933, No. 2, 113; S. I. Ilmenev, ibid., 1938, Nos. 11–12, 153. These results are summarised by E. W. Russell in *Imp. Bur. Soil Sci., Tech. Comm.* 37, 1938.

Surface mulches of organic matter—of straw, for example—improve the soil structure underneath them very considerably. Part of their action is undoubtedly that they protect the surface structure of the soil from raindrops, and part is also due to them keeping the surface soil moist for a longer period of the year, so allowing the soil fauna, helped by the micro-organisms, a longer season each year in which to build up a good stable structure. R. E. Stephenson and C. E. Schuster[1] have given an extreme example of this effect. A loam soil was kept under a straw mulch on some plots, in volunteer weeds and grasses in another, and kept clear of vegetation by scraping the surface of the soil in a third. After five years the percentage of water-stable aggregates larger than 1 mm. were 34, 17 and 3 respectively. This effect is large enough, however, to be readily noticeable in gardens.

THE EFFECT OF GROWING CROPS ON THE SOIL STRUCTURE

It is common knowledge that an old pasture field, when broken up, gives a soil having a very desirable structure for several years, and this is sometimes true after a grass or lucerne ley of only a few years' duration. The improvement effected by a ley in a given time depends on the ley itself, the soil and the climate.

The type of grass, and perhaps its management, influences the soil structure very strongly. Thus, in Canada, T. Pavlychenko[2] found that crested wheat grass (*Agropyron cristatum*) was an excellent structure improver on the Canadian prairies, a result also found by E. I. Vorobieva[3] in Russia, whilst slender wheat grass (*A. pauciflorum*) had little value. Similarly, W. S. Martin[4] in Uganda, J. R. McHenry *et al.*[5] in Nebraska, L. B. Olmstead[6] in Kansas, and I. P. Sarakhov[7] in the North Caucasian steppes have all demonstrated great differences between the structure-forming powers of different grasses. No comparable experiments have yet been made in England, though almost certainly our grasses differ considerably in this respect.

The cause of the difference between grasses as structural improvers is not fully understood, though the work of Pavlychenko and of T. M. Stevenson and W. J. White[8] in the Canadian prairies has established the importance of two of the factors responsible: the weight of root material produced and the strength of the roots, measured by the tensile force required to break them. The relative values of several species of prairie and pasture grasses as structure improvers depends

[1] *Soil Sci.*, 1945, **59**, 219; 1946, **61**, 219.
[2] *Natl. Res. Counc. Canada, Publ.* 1088, 1942.
[3] *Pedology*, 1939, No. 11, 81.
[4] *Emp. J. Expt. Agric.*, 1944, **12**, 21; *E. Afric. Agric. J.*, 1944, **9**, 189. Photographs of the soil under various grasses are given in each of these papers.
[5] *Nebraska Agric. Expt. Sta.*, 59*th Rep.*, 1946, p. 11.
[6] *Proc. Soil Sci. Soc. Amer.*, 1947, **11**, 89.
[7] *Pedology*, 1938, 1265.
[8] *Sci. Agric.*, 1941, **22**, 108.

on the amount of strong roots in the soil; very fine weak roots, even though they may be in great abundance, appear to be unimportant as soil-binding agents soon after the grassland has been ploughed out. Thus, crested wheat grass produces a greater length of roots over 0·1 mm. in diameter than slender wheat grass, and its roots, at comparable diameters, are stronger.

The only other plants besides grasses that appear to be efficient improvers of the soil structure are lucerne and some clovers; and the clovers in particular,[1] and perhaps under some conditions lucerne also,[2] may only be able to exert their greatest effect if grown with other grasses enhancing, in fact, the improvement brought about by the grass alone.

Suitable leys left down for three to four years may give a notable improvement in structure on some soils, and a few typical figures, taken from some results of G. I. Pavlov[3] and F. Y. Geltser[4] on irrigated land in Turkestan, are given in Table 96. However, much longer leys

TABLE 96

The Effect of a Ley on the Water-stable Crumbs in Irrigated Grey Desert Soils (Turkestan)

Per cent of water-stable crumbs larger than 1 mm.

Previous cropping	3 years' cotton	2 years' clover 1 year cotton	2 years' cotton 1 year clover	3 years' clover
	9	17	27	35
Previous cropping	Old meadow	6 years' lucerne	3 years' lucerne	Old arable
	79	30	20	4

than this are probably required on semi-arid soils where irrigation is not practised,[5] and also under some English conditions, for at Rothamsted one field that had been under ley for ten years showed no appreciable improvement in structure, though another that had been down for thirteen years had its structure definitely improved.

The effect of arable crops on the soil structure depends mainly on the amount of cultivation the soil receives. Thus, close-spaced crops, such as wheat, barley and oats, have little effect on the structure, whilst wide-spaced crops, such as maize and potatoes, that receive much inter-row cultivation, may cause a deterioration of structure, but this is probably due to the inter-row cultivations and not to the crops themselves. A proportion of the improvement in structure brought

[1] N. G. Iovenko, *Pedology*, 1939, No. 6, 37.
[2] E. I. Vorobieva, *Pedology*, 1939, No. 11, 81.
[3] *Proc. 2nd Int. Congr. Soil Sci.*, Moscow, 1932, **1**, 179.
[4] *Trans. 1st Comm. Int. Soc. Soil Sci., Soviet Sect.*, 1934, A2, 73.
[5] P. K. Ivanov. *Khim. Sotsial. Zemled.*, 1937, No. 8, 64; N. G. Iovenko, *Pedology*, 1939, No. 6, 37.

about by long leys may, in fact, be a consequence of the absence of cultivation operations during the period the land is under the ley.

The Mechanism of Crumb and Clod Formation

Crumb formation is mainly brought about in the field through the agency of clay particles, of cements such as certain types of organic matter and precipitated films of iron hydroxide,[1] and of living organisms. In normal arable loam soils the clay is the principal aggregating agency, unless there is more than 2 per cent. of organic carbon present,[2] and the clay content naturally controls the proportion of smaller water-stable crumbs more closely than that of larger.[3]

The exact way in which clay binds soil particles together is still not known. In most soils the clay forms a continuous network that enmeshes the silt and sand particles, though if the clay is kaolinitic,[4] and in some other circumstances not yet analysed,[5] the clay may actually bind the sand and silt particles together.

Clay particles aggregate together through the interaction of their exchangeable ions and the charges on their surfaces with the water molecules between the surfaces, and the binding forces increase as the relative orientations of neighbouring clay particles assume certain preferred positions. The evidence for the importance of orientation is still partly inferential.[6] Clay crumbs are larger and stronger if derived from deflocculated, or mainly deflocculated, clay pastes than from flocculated ones—conditions which X-ray evidence shows to be conducive to mutual orientation of neighbouring particles as contrasted with the conditions of more nearly random orientation of the neighbouring particles in flocs. Vilensky's result that working a soil at a certain optimum moisture content, which decreases with increasing pressure, and J. R. McHenry and M. B. Russell's[7] result that the aggregation of sand-clay mixtures can be increased by taking them through a certain limited number of wetting and drying cycles, are both explicable on this hypothesis, for in both cases conditions are conducive to helping clay particles take up preferred orientations with respect to their neighbours.

The importance of the exchangeable ions and water for aggregation

[1] J. F. Lutz, *Proc. Soil Sci. Soc. Amer.*, 1936, **1**, 43.
[2] L. D. Baver, *Amer. Soil Surv. Assoc.*, 1935, **16**, 55.
[3] For an example, see G. B. Clarke and T. J. Marshall, *Aust. J. Counc. Sci. Indust. Res.*, 1947, **20**, 162.
[4] J. B. Peterson, *Proc. Soil Sci. Soc. Amer.*, 1945, **9**, 37.
[5] For photographs of some of these conditions, see W. Kubiena, *Micropedology*, Ames, 1938.
[6] See, for example, D. I. Sideri, *Soil Sci.*, 1936, **42**, 381, 461; 1938, **46**, 129, 267; S. Hénin, *C.R.*, 1937, **204**, 1498; *Thesis, Univ. Paris*, 1938; E. A. Hauser and D. S. Le Beau, *J. Phys. Chem.*, 1938, **42**, 961; 1939, **43**, 1037.
[7] *Proc. Soil Sci. Soc. Amer.*, 1944, **8**, 71.

can be seen from E. W. Russell's[1] observations that strong clay crumbs can only be formed by drying clays dispersed either in water or in a few other polar liquids, such as some of the alcohols, and only then if the clay holds an appreciable number of fairly small exchangeable ions. Russell suggested the simplest way of explaining these results is to assume that clay particles are held together by bridges of orientated water molecules between the dissociated cations and the fixed negative charges on the surface of the clay particle, as shown diagrammatically in Fig. 43. This hypothesis, unfortunately, does not explain why clay crumbs when once dried are usually stable when put back in water.

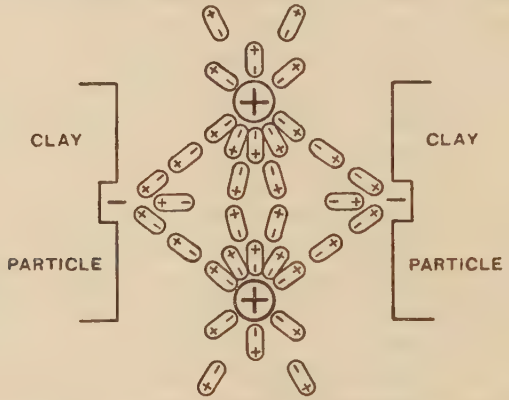


Fig. 43. Diagrammatic representation of two clay micelles held together as in a crumb.

On the other hand, R. K. Schofield has recently shown that the anomalous behaviour of dry crumbs of sodium and potassium clays to disperse water is explicable on the Debye-Hückel theory of electrolytes.

Strong clay crumbs are thus produced by drying clays from gels rather than flocs, for this encourages orientation. Hence, crumbs formed from a deflocculated paste of a sodium-saturated clay are harder than those from a paste of a calcium-saturated clay, as the latter is never so deflocculated; and adding a salt to the paste, by increasing the degree of flocculation, weakens the crumbs and so enables them to be broken up easier when dry, as can be seen from Plate V. Strongly flocculated pastes not only dry to give weaker crumbs, but the crumbs themselves tend to be built out of micro-crumbs which are probably the individual flocs that were present in the paste.

The relative effects of calcium and aluminium as exchangeable ions on the properties of the dry clay crumbs appear to be that as aluminium ions are more powerful flocculators than the calcium, so the crumbs of acid clays appear to be rather more crumbly, but also rather more

[1] *Phil. Trans.*, 1934, **233** A, 361.

water-stable than calcium ones, resulting in acid soils being more permeable and less easily dispersed than calcium soils.[1] But, as already discussed on p. 408, there is still doubt about the general validity of this conclusion.

The effect of the type of clay mineral present in the soil on the soil structure has not yet received much study. Montmorillonitic clays mixed with sand or silt give typical granular structure, and J. B. Peterson[2] has shown that soils rich in kaolinitic clay typically possess a characteristic laminar or platy structure, unless they contain much exchangeable calcium or mobile iron compounds, in which case they also possess a granular structure.

Clay, and possibly silt particles also, can bind certain components of the soil organic matter on their surface, as discussed on pp. 277–80, though what these components are is not known. Crumbs built out of these clay-humus particles are probably weaker, more crumbly or friable, and less sticky when wet than crumbs built out of the uncoated particles. But this important aspect of crumb formation has received little attention from research workers, so cannot be discussed any further.

The mechanisms by which organic matter can cause soil particles to aggregate into crumbs have not all been analysed out. As already pointed out, mere humus does not necessarily possess the power of binding soil particles together, and in fact organic matter often seems to improve the structure more by the process of its decomposition than by its presence. This is still a subject in urgent need of careful research, with few facts really firmly established, so the following discussion must be rather tentative.

Some of the components of the soil organic matter can unquestionably bind silt and clay particles into crumbs, though what these components are cannot yet be specified, as no work with carefully separated organic fractions has yet been done. The theory of humus formation which we have developed in Chapter 15 is that it is mainly composed of compounds derived from the oxidation of lignin, and of compounds produced by microbial metabolism. Some of the products of microbial metabolism, particularly polysaccharide gums[3] can be effective aggregators in the laboratory, and so also can some of the fats, waxes, and resins set free during the decomposition. There is still, however, some doubt about the importance of this factor in the field, as the concentration of gum required to produce good aggregation is between 0·1 and 0·5 per cent, which is probably considerably higher than it occurs in the

[1] J. F. Lutz, *Missouri Agric. Expt. Sta., Res. Bull.* 212, 1934; L. D. Baver and N. S. Hall, ibid., *Res. Bull.* 267, 1937; H. E. Myers, *Soil Sci.*, 1937, **44**, 331; J. B. Peterson, ibid., 1946, **61**, 247.

[2] *Proc. Soil Sci. Soc. Amer.*, 1945, **9**, 37.

[3] S. Winogradsky, *Ann. Inst. Pasteur*, 1929, **43**, 549; J. P. Martin, *Soil Sci.*, 1946, **61**, 157; M. J. Geoghegan and R. C. Brian, *Biochem. J.*, 1948, **43**, 5.

soil. Further, some workers have failed to demonstrate this aggregating effect of gums with the techniques they have used.[1]

It is also fairly certain, although there is little good evidence to prove the statement, that lignin-derived material can be an efficient aggregator. The mechanism through which it functions has not been proved, but metallic ions, such as calcium in neutral soils and aluminium in acid soils, probably play an essential role in linking the organic with the clay particles. If Sideri's views are correct (see p. 277), it is also possible that some organic fractions may help to improve the aggregation brought about by the clay particles through their alleged effect in causing clay particles in their neighbourhood to take up a common orientation.

Earthworms may be an important agent in producing a good soil structure, for their casts have a better structure than the bulk of the soil. The reasons for this better structure have not been worked out: it may simply be due to the clay, humic material and calcium salts all being intimately mixed with each other and with the larger silt and sand particles in the worm's gut, or it may be due to mucilages produced either by the worm or by bacteria in its gut. However, this improvement in structure is only small compared with that brought about by a ley. This is illustrated by the following results of A. K. Dutt,[2] which show the proportion of water-stable crumbs between 4·7 and 2 mm. in size in the top 3 inches of a silt loam soil carrying different crops and in the wormcasts formed on them.

	In top 3 inches of soil	*In wormcasts*
Arable	7	19
Three-year ley	46	58
Forest	59	68

The wormcasts on the arable soil have a better structure than the soil itself, yet the improvement brought about is much less than that brought about by a three-year ley; and the ley improves the structure of the whole soil whilst the casting-species of worms only improve the structure of a small proportion of the soil in an arable field. R. J. Swaby[3] has confirmed this observation on the Rothamsted soil, for he found that the casts of *A. nocturna*, the most common casting species there, have a good structure if produced on grassland but not if produced on arable.

The living organism itself can certainly hold soil particles on its surface, presumably through the surface containing some of the microbial gums just mentioned. Thus, M. L. Jackson, W. Z. Mackie

[1] See, for example, D. S. Hubbell and J. E. Chapman, *Soil Sci.*, 1946, **62**, 271; R. J. Swaby, *J. Gen. Microbiol.*, 1949, **3**, 236.

[2] *J. Amer. Soc. Agron.*, 1948, **40**, 407.

[3] I am indebted to Dr. Swaby for this information.

The water-stable soil structure built up by mixed populations of different types of micro-organisms (Rothamsted soil and glucose)

The break-up of the water-stable aggregates built up by the mycelia of the fungus *Aspergillus nidulans* (initial), after it had been heat-killed and the soil inoculated with a number of species of other organisms

(*p.* 417)

Soil crumbs held together by grass roots
(Ordinary chernozem on clay, 10–20 cm., Khrenovaia Station)
(*pp. 418, 527*)

and R. P. Pennington,[1] using an electron microscope, showed that many soil bacteria had clay particles clustered around them, and that some crumbs are simply aggregates of these tiny granules. Filamentous fungi can also bind soil particles on to their mycelia and so form water-stable clods that are porous and may be fairly strong,[2] but fungi differ very markedly in their power to do this. Thus, some species of *Cladiosporium*,[3] *Penicillium*[4] and *Trichoderma lignorum*[5] are good aggregators, whilst other species of *Penicillium* and *Rhizopus*[6] are poor. The mechanism of this structure formation is not settled: it may be predominantly a mechanical entanglement of soil particles between the fungal hyphae, or it may be this combined with micro-crumbs of silt and clay adhering to the hyphae. The actinomycetes tested have less power of forming crumbs than the effective fungi. These effects of micro-organisms in producing soil structure are illustrated in the top half of Plate XXI, which shows that the mixed culture of 22 species of soil fungi produced a definite, though weak, water-stable structure when growing in the Rothamsted soil to which a little glucose had been added; the mixed culture of 33 species of soil actinomycetes produced much less effect and the 66 species of soil bacteria still less.

F. Y. Geltser[7] has propounded a theory that the best structure is produced in a soil during the process of the bacterial decomposition of the fungal hyphae. She pictures the process by which the soil structure is improved when one adds decomposable organic matter as follows. The added organic matter is first attacked by fungi, and although this stage is often characterised by the production of dark-coloured gummy or humus-like material, this has little aggregating power. Then the fungal mycelia are attacked by small rod-shaped bacteria, and it is these bacteria that produce the active crumb-forming compounds, which are then excreted into the soil on the autolysis of the bacterial cells. These products are also dark-coloured and gummy, but combine with the clay particles, and it is these clay-humus particles that form the structure.

Some earlier results of J. G. Shrikhande[8] are in accord with Geltser's hypothesis. He was investigating the amount of mucilage produced

[1] *Proc. Soil Sci. Soc. Amer.*, 1947, **11**, 57.

[2] J. P. Martin and S. A. Waksman, *Soil Sci.*, 1940, **50**, 29; T. M. McCalla, *Proc. Soil Sci. Soc. Amer.*, 1947, **11**, 260.

[3] T. C. Peele, *J. Amer. Soc. Agron.*, 1940, **32**, 204.

[4] T. C. Peele and O. W. Beale, *Proc. Soil Sci. Soc. Amer.*, 1941, **5**, 33.

[5] I. I. Kanivets and N. P. Korneeva, *Pedology*, 1937, 1429; *Khim. Sotsial. Zemled.*, 1938, No. 6, 51.

[6] T. L. Martin and D. A. Anderson, *Proc. Soil Sci. Soc. Amer.*, 1943, 215.

[7] See, for example, her book (in Russian) *The Significance of Micro-organisms in the Formation of Humus*, Moscow, 1940. For an English summary of her views, see *Soils and Fert.*, 1944, **7**, 119.

[8] *Biochem. J.*, 1933, **27**, 1551.

by various organisms, as measured by the stickiness of the compost, when they were decomposing sterilised oat straw; and he showed that although neither the fungi nor the cellulose decomposing bacteria he used produced any mucilage when in pure culture, yet when the bacteria were inoculated into the straw after the fungi had been decomposing it for forty-eight days, they produced considerable amounts of mucilage, much more so than if they were inoculated into the straw at the same time as the fungi. The production of mucilage, therefore, appeared only when the bacteria began working after extensive fungal development, but the experiment did not show if the bacteria were then decomposing fungal tissue or straw residues. However, the experimental results of R. J. Swaby, illustrated in the bottom half of Plate XXI, do not accord with Geltser's hypothesis, for these show that the weak but water-stable structure produced by fungal hyphae is destroyed if they are attacked by mixed cultures of soil actinomycetes or bacteria.

The products micro-organisms excrete into the soil are not, however, necessarily beneficial. Some by-products, such as gums and mucilages will reduce the size of some of the soil pores, and this could be very undesirable if the soil is fine-textured, so possessing only a few pores down which surplus water can drain, particularly if these pores are near the lower size limit that permits water to move down at a useful rate. In such a soil the aerobic micro-organisms will develop most freely in these few pores, and if such by-products accumulate in them they will be narrowed sufficiently to have their permeability reduced appreciably.[1] There is no evidence that this effect is of any importance in temperate agriculture, though it may play an important role in keeping the permeability of paddy rice fields low. Further, these gums and mucilages may wet with difficulty after they have been dried, so that if they have been produced in abundance, as, for example, through large quantities of sugars or fats having been added to a soil, they will waterproof the crumbs, preventing them from being wetted, and sometimes completely preventing percolation through the soil.

The soil structure formed by grass roots is very characteristic. If a root is carefully removed from the soil it will be seen to have a large number of small crumbs hanging on to it, as is shown in Plate XXII, and many of these crumbs are clusters of very small crumbs or granules. This characteristic structure thus requires two mechanisms: one for producing the granules and the other for holding them together in clusters. As with so many aspects of soil structure, no adequate examination of these mechanisms has been made; but the root is probably directly responsible for holding the clusters, or at least the larger clusters,

[1] For examples, see L. E. Allison, *Soil Sci.*, 1947, **63**, 439.

together, whilst micro-organisms associated with the roots may be mainly responsible for the granules and for their small clusters.

The evidence for the importance of the root itself is derived from an examination of the rate at which this structure is produced by different types of grasses and the rate at which it decreases after the grassland has been ploughed out; the Canadian work, described on p. 411, illustrates the kind of evidence that is available at the present time. Once the roots holding the clusters together have decomposed, the clusters themselves disintegrate into their constituent granules. But this work does not show how the roots bind the granules together into clusters—it merely shows that the clusters cannot last any longer, and usually last for a shorter time, than the roots.

The evidence for the mechanism holding the fine soil particles together into granules is still meagre, but two, which are not mutually exclusive, have been postulated. One, developed by E. N. Mishushtin[1] in Russia, and D. S. Hubbell and J. E. Chapman[2] in America, is that the granules are formed by the fine soil particles adhering to living root hairs, fungal and actinomycete hyphae or even bacteria, as already discussed. This is a perfectly possible mechanism whilst the grass is growing, for the roots carry a large micro-organic population on and around them, but it is difficult to see on this picture how these granules can survive the ploughing out of the grass with the killing of the root hairs and the micro-organisms associated with the roots. The other mechanism, developed by F. Y. Geltser, is that the fine soil particles are cemented together by organic compounds produced by the micro-organisms living on the grass roots or in their immediate neighbourhood. Geltser considers that the most important cements are the autolytic products of some of the rhizosphere bacteria, and has recently claimed to have increased the speed with which a short-term ley can improve the soil structure by inoculating the seed with a culture of rhizosphere bacteria taken from the roots of leys growing on land having a very good structure.[3]

Our present knowledge about the processes responsible for structure formation in the soil is thus seen to be very limited. Clay is a powerful aggregator, but whether it is an acid or a neutral clay seems to make little difference to the stability of the crumbs, though excess calcium carbonate may weaken them mechanically so making them more mellow. Crumbs in which clay is the predominant cement probably possess little granularity: that is, they are usually fairly uniform in internal structure and do not appear to be built out of smaller granules.

Some humic fractions appear to be good aggregators giving weaker,

[1] *Pedology*, 1945, No. 2, 122. [2] *Soil Sci.*, 1946, **62**, 271.
[3] *Pedology*, 1945, No. 8, 421; *Trans. Acad. Agric. Sci.*, 1945, No. 3, 16.

more crumbly clods, that are less sticky when wet than clods held together by clay alone, though whether these clods or crumbs possess a granular structure or not has not been examined in detail. Some workers claim that the ideal cement for a good friable structure is clay particles coated with a suitable humic fraction, but this concept of the clay-humus complex as something more effective than the individual clay and humic particles has not yet been developed in detail.

Crumbs produced by grass rootlets, by some fungi, and possibly by some actinomycetes and bacteria, are very granular. Each granule consists of silt, clay and sometimes fine sand particles clustering around a rootlet or a bit of fungal hypha, and the crumbs are built out of clusters of such granules.

CHAPTER XXIV

THE DEVELOPMENT OF PLANT ROOTS IN SOIL

THE SOIL AFFECTS the plant primarily through its effect on the root system, and these effects should form the basis of this book. Unfortunately, investigations on the root systems of crops growing in the field are difficult to carry out, and in consequence our knowledge of the interaction between the soil, the roots and the aerial parts of the plant and, as important, between neighbouring root systems, is very scanty.[1]

Plant roots can have four separate functions: they absorb nutrients and water from the soil; they transport these from the areas where the absorption takes place to the stems; they may act as food storage organs, as, for example, in the root vegetables; and they may anchor the plant into the soil. The relative importance of these various functions depends on the plant and the local conditions.

Only a restricted part of the plant root takes part in nutrient and water absorption. The growing part of a plant root is usually white, but as it ages it turns brown, due to its outer layers becoming suberised, that is, to a corky material being deposited around them. These unsuberised white roots, except just for the area around their growing points, absorb water and nutrients,[2] but once suberisation begins their absorbing power falls very rapidly. But the absorbing power, both of these roots and the lightly suberised ones, is increased very considerably by the surface epidermal cells in the unsuberised layer, and by some of the lower epidermal cells where suberisation has just started, sending out root hairs into the soil that may be several millimetres long and about a hundredth of a millimetre in diameter.[3] Some results of H. J. Dittmer,[4] given in Table 97, illustrate the great contribution root hairs can make to the absorbing surface. Unfortunately, he only estimated the total surface of the roots; the surface capable of absorbing nutrients is considerably less.

The root hairs have a slimy surface and fine soil particles stick on to them. Thus, the root hair comes into very intimate contact with many soil particles. These root hairs and many of the unsuberised

[1] For accounts of the root system of crops, see J. E. Weaver, *Root Development of Field Crops*, New York, 1926, and other publications of his on this subject; E. C. Miller, *Plant Physiology*, (Chap. III) 2nd ed., New York, 1938; and for orchard trees in particular, W. S. Rogers, *J. Pomol.*, 1939, **17**, 67.

[2] P. Prevot and F. C. Stewart, *Plant Physiol.*, 1936, **11**, 509.

[3] For a description of root hair development, see K. Wilson, *Ann. Bot.*, 1936, **50**, 121.

[4] *Science*, 1938, **88**, 482; *Soil Conserv.*, 1940, **6**, 33.

roots[1] are often only very short-lived in the soil, as is illustrated in Plate XXIII for some feeding roots of the apple. Hence the plant may be continuously supplying the soil micro-organisms with a fairly readily available food supply in the form of dead and sloughed-off roots and root hairs.

TABLE 97

Surface Area of Roots and Root Hairs of Various Crops

Roots and Root Hairs in a cylinder of soil 3 in. diameter and 6 in. deep

	Roots		Root hairs			
	Length in feet	Surface area, sq. inches	Number in millions	Length in feet	Surface area, sq. inches	Per cent of soil volume occupied by roots and root hairs
Soybeans . .	95	63	6·1	1960	43	0·91
Oats . . .	150	49	6·3	26400	530	0·55
Rye . . .	210	78	12·5	55100	1190	0·85
Bluegrass. .	1260	330	51·6	169500	2450	2·80

These unprotected root hairs and unsuberised roots, which are responsible for the water and nutrient absorption of roots, are easily injured by unfavourable circumstances, such as poor aeration, lack of moisture, high acidity and its consequences of high soluble aluminium or manganese compounds. In so far as roots can grow in such soils, they have few root hairs and the new root tips suberise rapidly;[2] hence roots in such soils only have a very small absorbing system, so that the plants cannot withstand strongly drying conditions. Draining an inadequately drained soil, in fact, increases the drought resistance of the crops it carries, because it allows a greater development of the root area that can absorb water;[3] and water-logging a soil previously well aerated quickly kills all the root hairs and unsuberised roots, and, hence, usually the plant.

The rate of root growth depends on the temperature and the water and air supply in the soil, on the amount of carbohydrates the aerial parts of the plant translocate to the root system, and on the competition they suffer with other roots. Roots only grow in soils in which there are an adequate number of channels large enough for the root to penetrate. If the soil is too compact, then root growth is inhibited. Thus roots

[1] For method of observing this, and the photographs reproduced in Plate XXIII, see W. S. Rogers, *J. Pomol.*, 1939, **17**, 99.

[2] G. H. Bates, *J. Ecol.*, 1934, **22**, 271.

[3] For illustrations of this effect on the root system of coffee, see F. J. Nutman, *Emp. J. Expt. Agric.*, 1933, **1**, 271, 285.

cannot ramify in hard pans or other subsoil pans, and can only penetrate into them through pre-existing channels or cracks. Again roots cannot ramify throughout the bulk of a clay soil but are restricted to the cracks between the clay crumbs and to other channels.

Roots only grow actively in moist soils, although little is known about the maximum suction of soil water that permits root growth. Roots cannot usually grow into soil dried to its wilting-point moisture content, that is, whose water is under a suction of 7 to 10 atm.,[1] and W. S. Rogers[2] found that apple-tree roots will not grow in soils whose water is under a suction about half an atmosphere.

However, under some conditions the roots of some plants can grow in dry soils provided part of the root system is in moist soil.[3] The root system appears to transport water from the wetter regions and excrete it into the drier: the new growth appears, in fact, to take place in the zone wetted by excretion,[4] and under these conditions the roots can take up some nitrogen and perhaps some potassium from the dry soil they have wetted, though their power of taking up phosphates is more doubtful.

The root system of most plants only grows vigorously in well-aerated soils, and in these conditions it develops into a profuse, much-branched system of fine rootlets, many of which are short-lived. As conditions become unfavourable these rootlets are rapidly killed, or unable to develop, leaving a system of thicker, shorter and much less branched roots. Hence plants usually have a finer, more branched root system when growing in a sandy than in a clay soil.

The aeration of the soil affects the roots through three factors: the oxygen content in the soil air, the carbon dioxide content, and the contents of by-products of anaerobic decomposition, such as hydrogen sulphide, methane and hydrogen, which accumulate in the soil. The effects of these three factors have rarely been separated out in the root studies made in the field.

All roots are killed by high CO_2 concentrations, but many appear to tolerate 9 to 10 per cent for short periods. However, for optimum growth, concentrations of under 1 per cent are probably necessary.[5] Root development appears to be affected if the oxygen content falls below 9 to 12 per cent, depending on the crop, and to cease if it falls

[1] See, for example, A. H. Hendrickson and F. J. Veihmeyer, *Plant Physiol.*, 1931, **6**, 567; W. H. Metzger, *J. Amer. Soc. Agron.*, 1938, **30**, 80; A. S. Hunter and O. J. Kelley, *Plant Physiol.*, 1946, **21**, 445.

[2] *J. Pomol.*, 1939, **17**, 99.

[3] J. F. Breazeale, *Arizona Agric. Expt. Sta., Tech. Bull.* 29, 1930; with F. J. Crider, *Tech. Bull.* 53, 1934.

[4] A. S. Hunter and O. J. Kelley, *Plant Physiol.*, 1946, **21**, 445; G. M. Volk, *J. Amer. Soc. Agron.*, 1947, **39**, 93.

[5] J. Stoklasa and A. Ernest, *Zbl. Bakt.* II, 1905, **14**, 723; H. Lundegårdh, *Soil Sci.*, 1927, **23**, 417.

below 5 per cent.[1] The oxygen demands of the root, and its sensitivity to carbon dioxide concentration seem to increase as the temperature increases.[2] These results, however, do not apply equally to all crops. Rice, buckwheat and some willows, for example, grow well with a very restricted air supply around their roots. Tomatoes, and possibly peas and maize, need a very good air supply, and may even only make optimum growth if the air supply around their roots is either artificially improved or enriched with additional oxygen; the cereals and soybeans appear to come intermediate between these classes.[3]

The effect of the by-products of anaerobic conditions on plant roots has not been studied in any great detail. Hydrogen sulphide, even in very low concentrations, is toxic to most plant roots. Methane has been shown by J. Vlamis and A. R. Davis to have little effect on barley and appears to have improved the growth of rice. Hydrogen at low concentrations does not have any pronounced effect on the root development of plants, though it probably inhibits nitrogen fixation by the bacteria in the root nodules of leguminous plants.[4]

There is a close connection between the air conditions around the roots and their uptake of water and nutrients. H. T. Chang and W. E. Loomis[5] grew wheat, maize and rice plants in water solutions in quartz sand, and showed that increasing the carbon dioxide content of the solution reduced the uptake of water and some plant nutrients, particularly potassium and nitrogen, very considerably, whilst reducing the oxygen content of the solution and keeping the carbon dioxide content low, by bubbling through nitrogen gas, had little effect on the plants' uptake of either water or nutrients. On the other hand, L. P. Pepkowitz and J. W. Shive,[6] who grew soybeans and tomato plants in water cultures under conditions where the carbon dioxide concentration was kept low, found that the uptake of nutrients by these plants increased with increasing oxygen tension in the solution to a maximum and then decreased as the tension increased beyond this point.

The temperatures at which active root growth takes place have not been worked out in detail, but the roots of most commercial crops and trees need temperatures well above the freezing-point for active growth. Rogers,[7] for example, found that while apple-tree roots could make some growth in soils as cool as 35° F. or about 2° C.,[8] they

[1] See, for example, D. Boynton *et al.*, *Science*, 1938, **88**, 569; *Proc. Amer. Soc. Hort. Sci.*, 1943, **42**, 53; H. Vine, *Trop. Agric. Trin.*, 1942, **19**, 220.

[2] W. A. Cannon, *Science*, 1923, **58**, 331.

[3] E. E. Free, *Johns Hopkins Univ. Circ.* 198, 1917; W. A. Cannon, *Carnegie Inst. Publ.* 368, 1925; S. G. Gilbert and J. W. Shive, *Soil Sci.*, 1942, **53**, 143; 1945, **59**, 453; J. Vlamis and A. R. Davis, *Plant Physiol.*, 1944, **19**, 33.

[4] P. W. Wilson and R. H. Burris, *J. Bact.*, 1944, **47**, 410.

[5] *Plant Physiol.*, 1945, **20**, 221.

[6] *Soil Sci.*, 1944, **57**, 143.

[7] *J. Pomol.*, 1939, **17**, 99.

[8] E. B. Earley and J. L. Cartter, *J. Amer. Soc. Agron.*, 1945, **37**, 727, found a similar effect with soybeans.

did not grow actively until the soil had warmed up to 45°F. (7°C.). On the other hand, if the temperature becomes too high, growth again is checked, and this check is more severe the more unfavourable are other soil conditions, such as *p*H and aeration in particular.

The carbohydrates available for translocation to the roots for their growth appear to be a proportion of those not immediately needed by the aerial parts of the plant. Hence, any factor which allows carbohydrate production to go on but discourages aerial growth encourages active root growth. Thus, root growth does not take place when corn crops are ripening their seed, cotton plants are producing their bolls,[1] or fruit crops their fruit, for then the aerial parts are drawing heavily on the available carbohydrate supplies. An observation of F. J. Nutman[2] affords a good illustration of this effect. He showed that if coffee trees were allowed to overcrop, this so reduced the carbohydrate supply to the roots that insufficient feeding roots were produced to take up enough nutrients to mature the crop without harm to the tree. On the other hand, if a crop is prevented from ripening its seed, by removing its flower heads, for example, it may be encouraged to make extra root growth at this season, and this is the reason for the fruit-grower's practice of preventing newly planted trees from carrying a fruit crop.

The effects of fertilisers on root growth are mainly indirect, as their direct effects are usually on the rate of leaf growth and of carbohydrate production. If a crop is growing in a moderately fertile, moist soil favourable for root growth, and a fertiliser is added which remedies all nutrient deficiencies, the fertiliser may only increase top growth without any great effect on root growth: this is probably the most common effect of fertilisers on normal, reasonably fertile, agricultural soils. On the other hand, if the soil is very poor in a nutrient, all growth may be severely limited if the nutrient is not added. This is illustrated in Plate XXVI, which shows the stunted root system of an eight-year-old gooseberry bush growing on a poor sandy soil without added nutrients and the much deeper and extensive root system of a similar bush given a good dressing of farmyard manure before planting. Soils short of phosphate also illustrate this condition very well. Crops growing on such soils are stunted: they cannot produce much leaf, and hence much carbohydrate, so that the whole plant is starved. Adding phosphate increases leaf growth very considerably, which can now produce much larger quantities of carbohydrate which, in turn, allows much greater development in the root growth. Phosphates, as such, appear to have no specific effect in increasing root growth, in spite of many earlier statements to the contrary.

[1] For an example of this, see F. M. Eaton and H. E. Joham, *Plant Physiol.*, 1944, **19**, 507.
[2] *Emp. J. Expt. Agric.*, 1933, **1**, 271, 285.

This effect of adding a nutrient in short supply on the root development of a plant has the interesting consequence that the fertiliser, by increasing the root range of the plant, increases the amount of nutrients the plant can take up from the soil. Thus, J. W. T. Spinks and S. A. Barber,[1] using radioactive phosphorus P^{32}, showed that wheat plants take up more soil phosphate from a phosphate deficient soil if they are given superphosphate than if they are not. The authors unfortunately did not examine the effect of the superphosphate on the root development of the crop, but the easiest interpretation of their result is that given above.

The position in the soil where the fertiliser is put, however, affects the root development, for roots will ramify in the fertilised volume. Thus, putting the fertiliser in the subsoil will usually give a greater development of roots there than if it is all put in the surface soil.[2] This practice of deep fertiliser placement can also affect the drought resistance of plants growing on soils having poor subsoils in dry years, and this will be discussed further on pp. 445–8.

The effects of water supply on the root system are also indirect. Plants have usually only a shallow root system if grown in moist, fertile soils, for the aerial parts can use most of the carbohydrates produced. But a drought setting in after the plant has become established encourages a deep root system, for the first effect of water shortage in the soil is to reduce the rate of new aerial growth, hence, is to make more carbohydrates available for root growth. The classical examples of the effect of water supply on the depth of root development come from the American prairies.[3] The deepest root development is found in regions of moderate summer droughts but adequate winter rain, so that at the beginning of each growing season the soil is wet to a considerable depth, and during the summer there is enough rain to keep the prairie plants growing with the help of the water stored in the top few feet of soil. Under these conditions over 65 per cent of the species present will send their roots down to a depth of at least 5 feet, and many will reach 9 feet and a few 20 feet. This is illustrated in Plate XXIV[4] for a prairie at Hays, Kansas, when the root systems were examined during a period of years of average rainfall. It shows that a large proportion of the grass roots extended to 4–5 feet and many of the herbaceous plant roots went down to 6–8 feet. But as the rainfall decreases, so the rain wets the soil to a progressively shallower depth, and

[1] *Sci. Agric.*, 1948, **28**, 79.

[2] For red clover in New Jersey, see N. A. Ferrant and H. B. Sprague, *Soil Sci.*, 1940, **50**, 141; in Ohio, J. Bushnell, *J. Amer. Soc. Agron.*, 1941, **33**, 823. For sweet clover, see D. D. Smith, C. A. Woodruff and D. M. Whitt, *Agric. Engng.*, 1947, **28**, 347.

[3] See, for example, H. L. Shantz, *U.S. Dept. Agric. Bur. Plant Indust., Bull.* 201, 1911; J. E. Weaver, *Carnegie Inst. Publ.* 286, 1919; 292, 1920.

[4] F. W. Albertson, *Ecol. Monogr.*, 1937, **7**, 481.

as the root zone is mainly confined to this depth, it becomes shallower. This is shown in Plate XXV[1] for the same prairie as in XXIV but after a run of years of low rainfall. It shows clearly that the grass roots are now confined to the top 1–2 feet, and that the depth of rooting of the herbaceous plants is also much decreased. Weaver has also given an

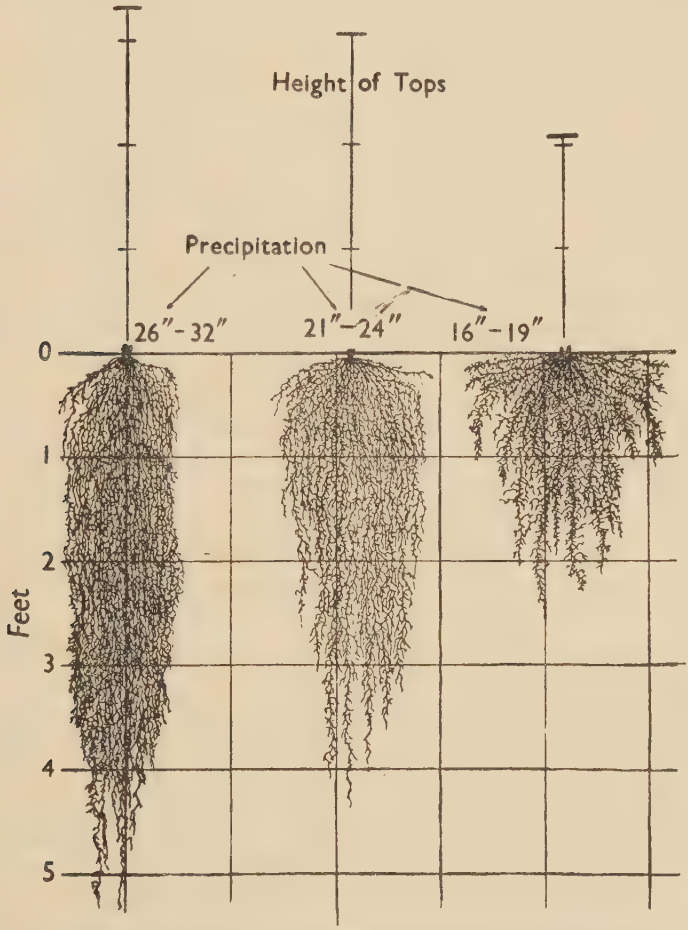


FIG. 44. The effect of the amount of rainfall on the depth of rooting of winter wheat. (Very fine sandy loam—silt loam in the Great Plains.)

example from the Great Plains of this effect of amount of rainfall on the depth of rooting of wheat, which is shown in Fig. 44.[2] As the rainfall decreases from 26–32 in. to 16–19 in., the root system decreases in depth from about 5 feet to 2 feet and the height of the wheat from just over

[1] J. E. Weaver and F. W. Albertson, *Ecol. Monogr.*, 1943, **13**, 1.
[2] *Root Development of Field Crops*, New York, 1926.

3 feet to just over 2 feet. On the other hand, as the rainfall increases, so the root system once again becomes more shallow, because the roots can find all the water they need in the superficial layers of the soil to carry the crop through the normal summer droughts. This is probably the principal factor responsible for plants usually being deeper rooted in light sandy than in clay or loam soils in the temperate region,[1] for the former will hold less available water per foot depth of soil than the latter, although the higher carbon dioxide concentration in the subsoil air of the loam or clay may also be in part responsible, in so far as it is not a reflection of the higher water-holding power of the soil.

It is therefore only when conditions favour deep rooting that plants can display their capacity to form deep roots. If conditions are continuously moist, all plants are shallow rooting and their root systems occupy the same layer of the soil. But as conditions increasingly favour deep rooting, the shallow-rooting species have their roots confined to the top layer and the deeper rooting have their root system increasingly developed in the lower layers, so that the root systems of different species are increasingly concentrated in their characteristic range of depths.

The dependence of the depth of the root zone on the water supply can be seen very clearly in irrigation work. Frequent light irrigations encourage shallow rooting, and infrequent heavy, deep rooting. Thus, C. A. Thompson and E. L. Burrows[2] found lucerne roots only penetrated 3 to 4 feet when the water was supplied in 2-inch irrigations, but to 5 feet if 5-inch irrigations were used; yet in the semi-arid deep silts of Nebraska they will penetrate 20 to 30 feet, and dry out the soil to that depth.[3] Deeper rooting, and hence heavy, infrequent irrigations are normally desirable in the earlier part of the growing season, mainly to allow the crop to tap as large a volume of soil as possible for nutrients, and to provide an insurance against periods of very high transpiration. These considerations naturally do not apply to market-garden crops grown with large amounts of fertiliser in regions of adequate water supply and only moderately high transpiration rates: here frequent light irrigations are preferable, as all carbohydrate production can then be used for producing more leaves and, hence, usually more saleable vegetables.

This dependence of root development on the surplus carbohydrates produced by leaves, as affected by the water supply, becomes of great importance in the correct management of pastures. Hard grazing of

[1] K. Linkola and A. Tiirikka, *Ann. Bot. Soc. Vanamo*, 1936, **6**, No. 6; V. J. Kivenheimo, ibid., 1947, **22**, No. 2.

[2] *New Mexico Agric. Expt. Sta., Bull.* 123, 1920.

[3] F. L. Duley, *J. Amer. Soc. Agron.*, 1929, **21**, 224; T. A. Kiesselback *et al.*, ibid., 1929, **21**, 241.

pastures reduces surplus carbohydrate production, for then all carbohydrates produced are needed to make good the loss of leaf. Hence, a hard-grazed pasture is typically shallow rooted; and hard grazing is, therefore, a practice only suited to moist climates. As the climate becomes more arid, the herbage must be allowed to grow longer, and hence the grazing must be lighter. Thus, W. R. Hanson and L. A. Stoddart[1] found on the semi-arid ranges of Utah the roots of bunch wheat grass (*Agropyron inerme*) only penetrated to about 30 cm. on over-grazed range and to about 60 cm. on protected range, and E. L. Florey and D. F. Thrussell, working on New Mexico ranges, found the roots of black and blue grama grasses (*Bouteloua eriopoda* and *gracilis*) penetrated to about 4 feet on properly grazed range, about 2 feet on over-grazed, and to under 1 foot on badly over-grazed.

The actual type of root system developed by a plant also depends to some extent on the soil conditions. The root system tends to be more branched and more compact in fertile than in poor soil, and if the roots are growing in soils of variable fertility, the habit of the root system varies with the fertility. Thus, if a plant is growing in a rather poor soil recently manured with farmyard manure, each pocket of manure will be filled with short, much-branched roots, and if the soil is stratified with layers of sand and clay, the root system will often be of the fertile type in the clay and the open type in the sand. However, if the clay is rather plastic, the root system will be confined to the spaces and cracks between the clay clods and crumbs, and because of the compression these roots will suffer during wet weather when these cracks seal up they are often flattened in cross section instead of being rounded.

The root systems of trees often illustrate this dependence of type on soil conditions. Many trees growing in natural forest with an undisturbed floor of litter tend to have an extensive much-branched root system filling the first few inches of the soil and a few deep tap roots. But if these trees are planted in open land where litter cannot accumulate, and particularly if this is done in rather dry regions, many of these trees will develop a root system filling several feet of the soil. F. Hardy[2] has given a good illustration of this with cacao. In humid conditions, or badly drained soils, it has a very superficial root system containing many mycorrhizas which, with the layer of leaf litter that accumulates, forms a mat on the surface. On well-drained soils, on the other hand, it has a deep root system, carrying no mycorrhiza and forming no surface

[1] *J. Amer. Soc. Agron.*, 1940, **32**, 278, and for further examples, see D. A. Stoddart and A. D. Smith, *Range Management*, New York, 1943. For the effect of different grazing methods on the depth of the root zone of pastures in W. European conditions, see E. Klapp, *Pflanzenbau*, 1943, **19**, 221.

[2] *Trop. Agric. Trin.*, 1944, **21**; 1943, **20**, 207.

mat. One of the most difficult problems in tropical agriculture concerns the management of plantation trees that cannot be made to develop a deep root system, for such trees suffer very badly from weed competition, drought and high surface soil temperatures. The principal method of minimising these harmful consequences of shallow rooting is to put a straw or vegetable mulch on the soil surface.[1] As will be explained on p. 584, this encourages favourable conditions for root development to develop under it, and consequently encourages all plants to develop a superficial root system which is of great importance if the principal plant nutrients are all concentrated in the surface layers.[2]

J. Baeyens[3] has summarised much of what has been said in the preceding paragraphs by emphasising two separate properties of the root system—what he calls the root surface and the root volume. The root surface measures the total absorptive area of the root, and the root volume is the volume of soil containing roots. The root system may have the same surface in a fertile well-watered soil as in a rather poor soil subject to drought, but in the first case the root volume would be small, the soil being filled with fine roots and the roots extracting nutrients intensively from this volume, and in the second the roots would be widely distributed throughout a large volume of soil and would only extract small quantities of nutrients from each unit volume of soil. Baeyens further emphasises, what has already been emphasised here, that the root volume is only large if the plant needs water or nutrients. Crops on a fertile moist soil always have a compact root system.

The actual rate of growth of plant roots in the soil varies widely. W. S. Rogers[4] finds 3 mm. a day a common figure for apple roots in the sandy loam soil at East Malling, rising to 9 mm. at times, whilst J. E. Weaver[5] quotes 10 mm. a day being common for grasses and up to 60 mm. a day for maize and squash plants in the silty soils of Nebraska. The total length of a plant's roots can be very large, particularly if it is growing by itself with no competition from other plants. Thus, T. K. Pavlychenko[6] found an isolated plant of wheat, rye or wild oats, growing on the sandy loam soil of Saskatoon, had produced 40 to 50 miles of roots by the time it came to maturity eighty days after emergence; but if these plants were grown in drills 6 inches apart with eighteen to twenty plants per foot, the root length was reduced

[1] For an account of management of the very shallow-rooting Robusta coffee trees in Uganda, see A. S. Thomas, *Emp. J. Expt. Agric.*, 1944, **12**, 191.

[2] I. W. Wander and J. H. Gourley, *Proc. Amer. Soc. Hort. Sci.*, 1943, **42**, 1.

[3] *Les sols de l'Afrique centrale*, Vol. I, 1938. Inst. Natl. Et. Agron., Congo Belge.

[4] *J. Pomol. Hort. Sci.*, 1939, **17**, 99.

[5] *Root Development of Field Crops*, 1926, New York.

[6] With J. B. Harrington, *Canad. J. Res.*, 1934, **10**, 77; *Sci. Agric.*, 1935, **16**, 151. Also *Ecology*, 1937, **18**, 62, and *Canad. J. Res.*, 1937, **15** C, 33, where the method used is described. For another illustration of the root system of rye, see H. J. Dittmer, *Amer. J. Bot.*, 1937, **24**, 417; for grasses, see T. K. Pavlychenko, *Natl. Res. Counc. Canada, Publ.* 1088, 1942.

about a hundredfold to about half a mile, although the reduction in the dry matter of the aerial parts of the plants was only about 15 per cent. As measured by length, the great preponderance of these roots are very fine, and these roots are reduced far more in proportion than the thicker ones when the root system suffers competition for space. Weeds can still further reduce the length of the root system. Unfortunately, no comparable work is available for normal English soils, and these lengths are probably much higher than would usually be found here, particularly in the moister parts of the country or on the heavier soils.

Plants growing in drills, or close spaced, not only have a shorter but also a more compact root system. A plant grown in isolation will have roots that spread over a very great area laterally, but if grown with neighbours the lateral spread will be very much restricted. On the whole, root systems of neighbouring plants, even of the same species, do not interpenetrate very much through the same volume of soil.

The total length and weight of the roots of different plants in a unit volume of soil depends on many factors, as already explained. But with these limitations in mind, Table 98, taken from some of T. Pavlychenko's results,[1] obtained in the central prairie states of the U.S.A. and Canada, is given to show the order of magnitude involved and the difference between grasses and crops. The samples were taken from prairies containing fairly pure stands of the grasses mentioned or from fields of the crops. The table gives some idea of the variation between the amount of roots formed by different grasses, for example, crested and slender wheat grass (*Agropyron cristatum* and *pauciflorum* respectively), and, as was explained on p. 411, this difference is reflected in the relative power of these two grasses for improving the tilth or crumb structure of the soil.

A review of the determinations that have been made on the weight of root residues under European conditions has been given by S. Gericke.[2] He shows that for the cereals the weight of roots left in the soil is about one-eighth the weight of the crop above ground, hence, on a 2-ton crop the root residues would weigh about 5 cwt. per acre, which is about half that given in Table 98, which, however, probably refers to a much lighter crop. The weight of roots produced by clovers and serradella, however, appear to be very variable, ranging from 2 to 50 cwt. per acre, whilst lucerne gives 1 to 1½ tons of roots per year. Grasses are like clovers in giving very variable weights of roots, again from 1 to 2 tons per year. The ratio of the weight of roots in a grassland soil to the weight of organic matter in that soil is discussed on p. 525.

[1] *Natl. Res. Counc. Canada, Publ.* 1088, 1942.
[2] *Bodenk. PflErnähr.*, 1945, **35**, 229.

TABLE 98

Quantity of Roots found in upper 10 cm. of Soil under Different Crops

Numbers and lengths of roots in metres or kilometres per half square metre
Weights of roots in hundredweights per acre

	Prairie grasses			Crops	
	Agropyron cristatum	*Agropyron pauciflorum*	*Poa pratensis*	Lucerne	Wheat near harvest
Underground Stems					
Length in m.	23·0	4·5	28·0	47·0	15·0
Weight per acre	24·6	6·7	17·4	16·5	4·2
Main Roots					
Numbers in thousands	11·7	8·0	16·3	—	1·5
Length in m.	935	563	1140	—	179
Average diam. in mm.	0·4	0·5	0·19	—	0·32
Weight per acre	9·3	5·1	10·6	—	2·7
Branches, First Order					
Number in millions	0·65	0·53	1·94	0·0054	0·082
Length in km.	39·2	21·2	75·5	0·25	4·30
Average diam. in mm.	0·09	0·1	0·04	—	0·09
Branches, Second Order					
Number in millions	7·85	2·28	10·57	0·152	1·10
Length in km.	55·0	16·0	95·1	4·85	15·4
Average diam. in mm.	0·04	0·03	0·018	—	0·03
Branches, Third Order					
Number in millions	3·13	1·15	—	0·738	0·83
Length in km.	9·5	3·1	—	5·16	6·67
Average diam. in mm.	0·01	0·007	—	—	0·008
All Branches					
Number in millions	11·6	3·96	12·6	0·895	2·02
Length in km.	103·4	40·2	170·6	10·3	26·4
Weight per acre	14·0	7·5	16·0	—	4·2
All Roots					
Weight per acre	47·7	19·4	44·0	19·0	11·1

Apple-tree roots growing in a silt loam, photographed on the 6th, 25th and 35th day after the two thick roots had first entered the area (about 4 times natural size)

(p. 422)

The root systems of plants in a typical short-grass prairie after a run of years with average rainfall (Hays, Kansas)

(*p.* 426)

The root systems in the same area after a run of drought years

Al Allionia linearis, Ap Aristida purpurea, Aps Ambrosia psilostachya, Bd Buchloe dactyloides, Bg Bouteloua gracilis, Kg Kuhnia glutinosa, Lj Lygodesmia juncea, Mc Malvastrum coccineum, Pt Psoralia tenuiflora, Sm Solidago mollis, Ss Sideranthus spinulosus

(*p. 427*)

The effect of nutrients on the root development of eight-year-old gooseberry bushes in a sandy soil (Wrotham Heath, Kent)

(*Left*) No manure; (*Right*) with 45 tons per acre of farmyard manure in the year of planting. The roots of the manured bush, resting on the ground, should continue downwards. The measure is marked in feet

(*p. 425*)

CHAPTER XXV

THE UPTAKE OF NUTRIENTS FROM THE SOIL

The Absorption of Nutrients and Water by Plant Roots

PLANT ROOTS ABSORB nutrients from the soil in the form of anions and cations. The mechanism by which these are absorbed is still uncertain, but the absorption of the nutrient ions must involve an expenditure of energy, as they are up to a hundred times more concentrated in the cell sap than in the soil solution.[1] On the other hand, there is no theoretical need for energy to be required for the absorption of water, as the osmotic pressure of the cell sap is between 10 and 20 atm. higher than that of the soil solution in most British soils.[2]

The source of the energy expended in nutrient absorption is presumably carbohydrates which are oxidised in the absorbing cells, for these cells require a constant supply of oxygen and removal of carbon dioxide if they are to carry out this process.[3] Water absorption also appears to require a good oxygen supply, and hence to be an energy process, but this may simply be that unless the cells are able to be active they cannot maintain their semi-permeable membranes. Absorption of nutrients and water is thus part of the respiration processes of the root cells, which can therefore only function in a soil that is adequately aerated, and they usually cease to function before they are physically injured by unfavourable conditions. There are, however, a few exceptions to this, as some plants, for example, rice,[4] can allow oxygen from the atmosphere to diffuse through special cells in their stems and roots to the absorbing cells.

The respiration of root cells and their ability to absorb nutrients may, however, be to two aspects of the same process if H. Lundegårdh's theory[5] of these processes is basically correct. This theory pictures the processes involved as follows. Respiration in a living cell involves the transfer of electrons from inside to outside the cell, and the enzyme system that effects their transfer across the living membrane of the cell

[1] For a recent theory, see H. Lundegårdh, *Nature*, 1946, **157**, 575.

[2] D. R. Hoagland and A. R. Davis, *Protoplasma*, 1929, **4**, 610; for further references, see O. C. Magistad, *Bot. Rev.*, 1945, **11**, 181.

[3] V. Iljim, *Jahr. wiss. Bot.*, 1927, **66**, 947; F. M. Eaton, *J. Agric. Res.*, 1942, **64**, 357.

[4] See the work of J. W. Shive and his co-workers, *Soil Sci.*, 1942, **53**, 143; 1944, **57**, 143; D. R. Hoagland and T. C. Broyer, *J. Gen. Physiol.*, 1942, **25**, 865; for review, D. I. Arnon, *Ann. Rev. Biochem.*, 1943, **12**, 493; D. R. Hoagland, *Lectures on the Inorganic Nutrition of Plants*, Waltham, Mass., 1944.

[5] *LantbrHögsk. Ann.*, 1940, **8**, 234; *Ark. Bot.*, 1945, **32** A, No. 12; *Nature*, 1946, **157**, 575; *Ann. Rev. Biochem.*, 1947, **16**, 503. See also R. N. Robertson and M. J. Wilkins, *Aust. J. Sci. Res.*, 1948, **1** B, 332.

at the same time effects the transfer of a corresponding number of anions from outside to inside the cell, to maintain electric neutrality. Further, the source of electrons in the cell are hydrogen atoms, which by giving away an electron become hydrogen ions, and the acceptors of the electrons outside the cell are hydrogen ions which become hydrogen atoms. This process is thus equivalent to transferring hydrogen from, say, carbohydrate molecules in the cell, leaving as an end-product carbon dioxide, to, say, oxygen molecules outside the cell with the consequent formation of water, which is another way of considering the process of aerobic respiration. Electron transfers thus increase the hydrogen ion concentration inside the cell and decrease it outside, and this in turn causes some of them to exchange with cations outside the cell across the cell membrane. Thus the process of cation uptake is a base, or cationic exchange—a process which, in fact, is not confined to the excretion of hydrogen ions.

Two consequences follow from the assumption that cation uptake is a base exchange process. In the first place it is not a one-way process. Cells can lose, or excrete, cations other than hydrogen ions, and this has been demonstrated experimentally (see p. 445). In the second place one would expect the root cells to absorb simple small cations in approximately the proportions that they occur outside them. But this does not imply that the cations will be present in this proportion in the plant tissues, for their rate of transfer from the root cells to the plant sap depends considerably on the individual ions. Thus, potassium appears to move more quickly than the other common cations, and incidentally nitrate more so than most other anions, from the soil into the sap,[1] and these are the two ions that appear to be taken up in appreciably higher proportion than their relative abundance in the soil would suggest.[2] On the other hand, aluminium[3] and related ions and some rare earths[4] are taken up by the roots but are hardly translocated at all by most plants.

Plants differ, however, in their power of taking up some cations, or at least in their power of transferring them into their aerial portions. H. Collander[5] found that these differences between plants was most marked for the uptake of sodium and magnesium, some species being able to take up sixty times as much as other species. Thus, halophytes could nearly all take up very large quantities of sodium, whilst buckwheat, maize and sunflower could take up very little. Again, some plants, particularly some members of the *Chenopodiaceae*, could absorb

[1] H. Lundegårdh, *Nature*, 1946, **157**, 575.
[2] R. H. Bray, *J. Amer. Chem. Soc.*, 1942, **64**, 954; C. E. Marshall, *Missouri Agric. Expt. Sta., Res. Bull.* 385, 1944.
[3] G. E. Hutchinson, *Quart. Rev. Biol.*, 1943, **18**, 1.
[4] L. Jacobson and R. Overstreet, *Soil Sci.*, 1948, **65**, 129. [5] *Plant Physiol.*, 1941, **16**, 691.

large quantities of magnesium. On the other hand, all plants had about the same power of accumulating potassium when growing in potassium-rich conditions.

The distribution within the plant of the different ions taken up by the roots depends on the part of the plant being studied. The mineral composition of the seed or fruit is more a characteristic of the plant than of the abundance of the ions in the soil, whilst that of the root depends more on their abundance in the soil than on the plant; the composition of the leaves and stems is intermediate. Thus, as G. T. Nightingale[1] has shown for pineapples, and D. I. Arnon and D. R. Hoagland[2] for tomatoes, the developing seed or fruit takes just those quantities of mineral from the main reservoir available in the roots and vegetative system needed to give it its characteristic mineral composition. Fruits are in fact relatively high in potassium and low in calcium, perhaps because the plant contains much higher reserves of mobile potassium than calcium in its tissues, for much of the calcium in a plant is relatively immobile.[3]

The fact that the composition of the leaves of a plant reflect to some extent the nutrient conditions in the soil can be used by agricultural advisers to determine, from the analysis of an unhealthy leaf, if the trouble is due to a deficiency of any particular nutrient or to a lack of balance between the nutrients.[4] It has also great agricultural importance, for the leaves of grasses and legumes form the primary food of the world's sheep and cattle. Now the grazing animal requires not only protein and carbohydrate from these leaves, but also its supply of minerals, hence the feeding value of pastures or hay can depend on the soils on which they are grown. The best-known example of this on a world-wide scale is the phosphate content of the herbage, which is usually a fairly good reflection of the available phosphate supply in the soil.[5] There are considerable areas of very phosphate-deficient soils, particularly in South Africa and Australia, which carry a grass or prairie vegetation that has such a low phosphorus content that the animals grazing on them suffer from acute phosphorus-deficiency diseases[6] (Table 99).

The mineral content of plant leaves can thus be affected within limits by suitable use of fertilisers. Thus, the phosphorus content of grass leaves can be doubled, and at the same time the calcium content

[1] *Bot. Gaz.*, 1942, **103**, 409; 1943, **104**, 191; *Soil Sci.*, 1943, **55**, 73.
[2] *Bot. Gaz.*, 1943, **104**, 576. [3] T. G. Mason and E. J. Maskell, *Ann. Bot.*, 1931, **45**, 125.
[4] For a recent review of the power and limitations of these methods of leaf analysis, see D. W. Goodall and F. G. Gregory, *Imp. Bur. Hort., Tech. Comm.* 17, 1947.
[5] For an extensive series of soil and plant analyses illustrating this, see G. S. Fraps and J. F. Fudge, *Proc. Soil Sci. Soc. Amer.*, 1938, **2**, 374; *Texas Agric. Expt. Sta., Bull.* 582, 1940.
[6] For corresponding American results, see K. C. Beeson, *Soil Sci.*, 1945, **60**, 9; *Bot. Rev.*, 1946, **12**, 424.

increased by 50 per cent by adding superphosphates to a phosphate-deficient pasture,[1] and this may increase the nutritive value of the fodder, as has recently been shown very strikingly in some feeding experiments on differently manured hays by W. A. Albrecht and his co-workers.[2]

TABLE 99

Per cent P in the Dry Matter of Grassland Herbage

	Good soils		Poor soils
Romney Marsh[3] . .	0·26	Transvaal Veld[5] . .	0·04
Scotland[4] . . .	0·32	Bechuanaland[6] . .	0·02
		Victoria[7] . . .	0·04

The dependence of the relative concentrations of the cations in the leaves of a plant on their relative concentrations in the soil as available or exchangeable ions has now been put on a semi-quantitative basis for several crop plants. The following factors are relevant: the crop studied, the relative proportions of these cations in an available form in the soil, the total concentration of these cations in the soil, the type of clay, and the relative contribution of the clay and the organic matter to the base-holding power of the soil.

In the first place plants differ very considerably among themselves in the proportions of potassium, magnesium, calcium and sodium their leaves contain when they are growing in the same soil, in the minimum concentrations of these ions needed for healthy growth, and in the maximum concentrations at which any particular ion can occur. Thus, A. Mehlich and J. F. Reed[8] found that for crops growing in a given soil the relative concentration of calcium to potassium and magnesium in the leaf is lower for oats and timothy than for alsike, red clover and soybeans, and is lower in these than for lucerne, cotton and turnips. This property is not quite that discussed for C. A. Bower and W. H. Pierre (see p. 66), as they were interested in the minimum concentrations of these ions needed for optimum growth, but it should be very similar. Unfortunately, the two groups of workers had too few crops in common for a close comparison to be made of the responsiveness of a

[1] W. Godden, *J. Agric. Sci.*, 1926, **16**, 98. Similar results were obtained by G. Paturel in France, *J. Agric. Prat.*, 1911, **21**, 12; also A. E. V. Richardson in Victoria, *J. Dept. Agric. Victoria*, 1924, **22**, 193, 257; in both cases the unmanured herbage contained only 0·1 per cent P, while that receiving phosphatic manuring contained distinctly more.

[2] *Proc. Soil Sci. Soc. Amer.*, 1942, **6**, 252; 1943, **7**, 322; 1944, **8**, 282.

[3] A. D. Hall and E. J. Russell, *J. Agric. Sci.*, 1912, **4**, 339.

[4] J. B. Orr, *Minerals in Pastures*, p. 13, 1929, London.

[5] H. Ingle, *J. Agric. Sci.*, 1908, **3**, 22.

[6] A. Theiler, *Union of South Africa, 11th and 12th Vet. Repts.*, 1927.

[7] H. Kincaid, *Proc. Roy. Soc. Victoria*, 1911, **23**, 363.

[8] *Soil Sci.*, 1948, **66**, 289.

crop to a potassic fertiliser on a calcareous soil with the relative concentration of potassium to calcium in its leaves.

The effect of altering the concentration of any one cation in the soil whilst keeping the others constant on the cation concentrations in the leaves is that, in general, increasing the calcium in the soil depresses the magnesium in the leaves more than the potassium; increasing the magnesium depresses the calcium more than the potassium; and increasing the potassium may depress the calcium more than the magnesium, or may decrease them about equally. An example of these effects is given in Table 100 for bluegrass (*Poa pratensis*), a plant having a low calcium-potassium ratio in its leaf, and for sweet clover, which has a high ratio.

TABLE 100

The Effect of a given Increase of a Cation in the Soil on the Composition of the Plant[1]

Milli-equivalents of cation per 100 grams dry matter in the plant

Added to soil	Bluegrass				Sweet clover			
	Ca	Mg	K	Total	Ca	Mg	K	Total
Basal .	35	42	54	131	102	62	47	211
+Ca .	41	37	53	131	124	57	45	226
+Mg .	30	63	50	143	100	97	42	239
+K .	23	24	95	142	72	38	102	212

This result can equally well be expressed in the statement that the plant tends to maintain its potassium content more stable than its magnesium, and its magnesium than its calcium, as the concentration of other cations around the plant roots varies.

It is sometimes possible to predict, from a knowledge of the composition of the exchangeable ions in the soil, the proportion of these ions in the leaves of the crop, and on the whole it is found that the ratio of potassium to calcium is much higher in the leaf than in the soil and that of magnesium to calcium somewhat higher; but the factors for converting from the soil ratio to the plant ratio are very dependent on the plant but not very dependent on the soil, or on the actual proportions of the exchangeable ions present. However, it is probable that a more accurate prediction can be made if, instead of determining the ratio of the exchangeable ions in the soil, one shakes up the soil with a small amount of hydrochloric acid, enough to supply hydrogen ions for only a small fraction of the exchangeable bases. Then for plants with a moderate

[1] C. E. Marshall, *Missouri Agric. Exp. Sta., Res. Bull.* 385, 1944. The results given are for the mean of the crops on two soils and at two levels of calcium supply.

calcium demand, the relative concentrations of calcium to magnesium are about the same in the acid extract and in the leaf, but the relative potassium content of the leaf is higher, by a factor of between 2–4,[1] than in the acid extract of the soil.

The Soil Solution

The water in the soil contains soluble salts, and hence whenever this aspect of the soil water is relevant, it is usually known as the soil solution. As has often happened in the history of agricultural science, the first investigations on the chemical composition of these dissolved salts was made in France. Th. Schloesing[2] in 1866 devised a method of collecting the soil solution based on displacement by water. He placed 30 to 35 kg. of freshly taken soil containing 19·1 per cent of water in a large inverted tubulated bell jar and poured on it water, coloured with carmine, in such a way as to simulate the action of rain. The added water at once displaced the soil water and caused it to descend so that it could be collected: a sharp horizontal line of demarcation between the added and the original water persisted throughout the experiment, even when eight days were occupied in the descent. A typical analysis of the displaced liquid in milligrams per litre was:

SiO_2	Nitric acid	Carbonic acid	CaO	MgO	K_2O	Na_2O	Sulphuric acid	Chlorine	Organic matter
29·1	305	118	264	13·5	6·9	7·8	57·9	7·4	37·5

The solution, therefore, contained about 850 mgm. of material per litre, that is, its concentration was about 0·08 per cent, or about 160 parts per million of the soil was present in the solution.

Three groups of methods have been in fairly recent use, and all give solutions having reasonably similar compositions. J. S. Burd and J. C. Martin[3] devised a method, still in use to-day, based on forcing water through a tall column of soil, under a pressure of 7 atm. (100 lb. per sq. in.) and collecting the effluent in small lots. The first few lots have similar compositions and are taken to represent the soil solution. A second method is based on dispersing the soil solution in a large volume of inert liquid, such as paraffin,[4] and separating out this liquid and analysing the solution it contains. This

[1] See, for example, R. H. Bray, *J. Amer. Chem. Soc.*, 1942, **64**, 954; T. B. van Itallie, *Soil Sci.*, 1938, **46**, 175; 1948, **65**, 393; A. Mehlich, *Soil Sci.*, 1946, **62**, 393; with J. F. Reed, ibid., 1948, **66**, 289.

[2] *C.R.*, 1866, **63**, 1007; 1870, **70**, 98.

[3] *J. Agric. Sci.*, 1923, **13**, 265.

[4] A. G. Doyarenko, *Versuchsfeld f. allg. Ackerbau. Landw. Akad.*, Moscow, 1924–7, **2**, 1.

is based on the assumption that the solution dispersing in the paraffin has the same composition as the soil solution. A modification of this is to use ethyl alcohol or glycol,[1] and to assume that the solution as a whole dissolves and that no extra salts come into solution. A third method, recently introduced by L. A. Richards,[2] is based on putting a thin disk of soil in a pressure cell, sealed at the bottom with a supported cellophane membrane, and forcing the soil water through the membrane by applying a gas pressure of 16 atm. This last method gives a solution from which the phosphate has been removed, for it is held back by the cellophane membrane.

The composition of the soil solution depends on the moisture content of the soil, the growth of the crop in the soil, and the activity of the microbial population. These factors are difficult to separate out in the field, and it is not certain how far results obtained in the artificial conditions of the laboratory apply to the field. The main results, however, are clear enough, and reasonable enough, for their general validity to be accepted.

The effect of the moisture content of the soil on the composition of the soil solution is as follows:[3]

(*a*) The concentration of nitrate and chloride varies inversely as the moisture content, indicating that all these anions present in the soil are in the soil solution.

(*b*) The concentration of phosphate, though varying from soil to soil, is independent of the moisture content, being usually about 1 to 3 parts per million. The soil solution is, therefore, presumably saturated with phosphate.

(*c*) The relative proportions of the cations in the soil solution depend on their concentration. Adding water to it, so diluting it, causes a smaller proportional decrease in the monovalent than divalent ions (see p. 111). Since in most soils calcium is the predominant cation in the soil solution, this means its concentration varies approximately inversely with that of the soil solution, since the total amount of anions in solution remains about constant, and that as the solution becomes more concentrated so the potassium and sodium ion concentrations rise in proportion more slowly than that of the anions or of the calcium.

The effect of the growing plant is to deplete the soil solution of much of its nutrient material, particularly its nitrate, as already discussed on p. 293. An example of this depletion, showing how it affects some nutrients much more than others, is given in Table 101, taken from

[1] A. Kawe, *J. f. Landw.*, 1932, **80**, 87.
[2] *Soil Sci.*, 1941, **51**, 377; with R. F. Reitemeier, ibid., 1944, **57**, 119.
[3] J. S. Burd and J. C. Martin, *J. Agric. Sci.*, 1923, **13**, 265.

some work of Burd and Martin.[1] It shows the composition of the soil solution before a crop of barley is sown, after harvest, and just before the next crop is put in; the results have been adjusted to the standard moisture content shown in the first column. The large recovery noticeable in the following spring is very dependent on the soil conditions and on the nutrient reserves in the soil.[2]

TABLE 101

The Effect of the Growing Crop on the Composition of the Soil Solution

Solutions displaced by water from cropped soils at beginning (April) and end (September) of growing season (1923) and at the beginning of the next growing season (1924)

Soil	Date	pH	Parts per million of displaced solution								
			NO_3	HCO_3	SO_4	PO_4	Ca	Mg	Na	K	Total solids
No. 7:	Apr. 30, 1923	7·4	149	83	561	1·1	242	91	42	21	1190
12·5 per cent	Sept. 4, 1923	7·6	58	155	432	0·6	193	47	40	9	935
moisture	Apr. 28, 1924	7·6	252	142	699	0·6	336	76	59	12	1527
No. 11:	Apr. 30, 1923	8·2	173	160	671	3·3	222	97	87	41	1454
12·4 per cent	Sept. 4, 1923	7·6	16	234	598	1·2	192	64	44	22	1171
moisture	Apr. 28, 1924	8·1	263	259	785	2·9	276	94	78	35	1793

The effect of the micro-organisms is to help bring about this replenishment of the soil solution, particularly the replenishment of the nitrate and sulphate, for, if depleted soils are stored in contact with toluene, so microbiological activity is suppressed, and little or no replenishment takes place.[3]

The soil solution of normal leached agricultural soils under normal conditions of moisture content is found to contain up to 0·05 per cent of soluble matter, and the osmotic pressure of the solution varies from 0·2 to 1 atm., being higher the nearer the moisture content is to the wilting-point. Thus, even at the wilting-point the soil solution is very dilute, and has an osmotic pressure far lower than the 10 to 20 atm. of the root sap. Hence, the transfer of water and nutrients from the soil to the root requires a definite expenditure of energy, which the roots of most agricultural plants can only incur if they have access to an adequate supply of oxygen.

The soil solutions of arid and of semi-arid irrigated soils differ from

[1] *Soil Sci.*, 1924, **18**, 151. See also *Hilgardia*, 1931, **5**, 455, for a summary of much of their work.

[2] See D. R. Hoagland, *J. Agric. Res.*, 1918, **12**, 369, for a soil showing little recovery.

[3] D. R. Hoagland, *Hilgardia*, 1925, **1**, 227; J. S. Burd, *Soil Sci.*, 1925, **20**, 269.

that in leached soils by their higher salt contents; for in these soils calcium and sodium salts of sulphates and chlorides, in particular, accumulate,[1] with the consequence that the osmotic pressure of the soil solution is no longer negligible, but may become high enough to limit crop growth. It has the further consequence that as the soil dries the osmotic pressure of the soil solution rises, so that soils containing so much soluble salts that they are on the margin of profitable cultivation need to be watered frequently (p. 552), for the crop can only extract a small proportion of the water held between field capacity and the direct suction corresponding to *p*F 4·2 before the osmotic pressure has risen high enough to affect the crop. Thus, as pointed out on p. 377, in such soils only a small amount of the water defined as available on the suction basis is, in fact, readily available; in fact, the concept of available water, based on suction measurements, ceases to be valid once the osmotic pressure of the soil solution at the wilting-point becomes appreciable.

The Sources from which Plant Roots Extract Nutrients

There are three possible sources from which roots can extract their nutrients: the soil solution, the exchangeable ions, and the readily decomposable minerals; and it is very difficult to separate out the relative importance of these three sources for any particular plant. C. G. B. Daubeny, in a classical investigation made over a hundred years ago,[2] showed that only a part of the total supply of plant nutrients was available to the plant. But it was soon found that there was no sharp division between available and unavailable plant foods in the soil, for different species of plants had differing powers of extracting the nutrients. The older investigators attributed the different "feeding powers" of plants to differences in the total acidity of their sap; thus they assumed the reason that leguminous plants could often extract more nutrients from a soil than could the grasses was because they had a more acid root sap,[3] although later work showed that, if anything, they have a less acid sap.[4]

J. von Liebig first introduced the idea that the exchangeable bases in the soil are the primary source of nutrients for the plant, which he expressed in the following words: "The power of the soil to nourish cultivated plants is, therefore, in exact proportion to the quantity of nutritive substances which it contains in a state of physical saturation.

[1] O. C. Magistad and R. F. Reitemeier (*Soil Sci.*, 1943, **55**, 351) give analyses of the soil solution of some saline soils at their field capacity.
[2] *Phil. Trans.*, 1845, 179.
[3] B. Dyer, *Trans. Chem. Soc.*, 1894, **65**, 115; *Phil. Trans.*, 1901, **194**B, 235.
[4] H. Kappen, *Landw. Vers.-Stat.*, 1918, **91**, 1; W. Thomas, *Plant Physiol.*, 1930, 5, 443.

The quantity of other elements in a state of chemical combination distributed through the ground is also highly important, as serving to restore the state of saturation, when the nutritive substances in physical combination have been withdrawn from the soil by a series of crops reaped from it."[1] This hypothesis that the exchangeable bases are the principal source of these nutrients for the plant was extended by W. Knop[2] in a remarkable investigation of considerable historic interest, and also by O. Kellner.[3] M. Whitney in 1892,[4] and later in collaboration with F. K. Cameron,[5] developed the hypothesis that the plant obtains its nutrients from the soil solution, and hence that a study of the nutrients in the soil solution should lead to an accurate assessment of the fertility of the soil.

Thus, the early investigators had shown that there are three sources from which plant roots can extract their nutrients: the soil solution, the exchangeable ions, and readily decomposable minerals. These are not three independent sources, for the soil solution is in equilibrium with the exchangeable bases and the phosphate compounds in the soil; and if any nutrient except nitrate is removed from the solution, at least a part of this loss will be made good from the non-soluble nutrient reserves in the soil. The solid material of the soil, in fact, keeps the soil solution well buffered both for *p*H and for all nutrients except nitrates. But since the power of different plants to extract nutrients from a soil differ, the roots must presumably be able to use at least some proportion of the nutrients contained in the more readily decomposable minerals in the soil.

The mechanism by which roots obtain ions from readily decomposable minerals is principally by excreting carbon dioxide, which forms a solution of carbonic acid on the surface of the mineral, a hypothesis originally due to F. Czapek in 1896[6] and further established by J. Stoklasa.[7] This, however, is not the only mechanism for extracting nutrients that are not dissolved in the soil solution. Direct exchange of hydrogen ions excreted by the roots and root hairs with cations held by the mineral particles, as postulated by H. Jenny and R. Overstreet, is another possible mechanism, and excretion of organic acids is again possible, and is the most likely mechanism by which a few plants, such as lupins, can use difficultly available phosphates (p. 461).

An example of the soil's power to make good the loss of a particular nutrient from the soil solution is given in Table 102, which shows that the total potassium taken up by a crop is very much greater than the

[1] *Natural Laws of Husbandry*, London, 1863.
[2] *Die Bonitierung. der Ackererde.*, Leipzig, 1871.
[3] *Landw. Vers.-Stat.*, 1886, **33**, 349.
[4] *U.S. Weather Bur. Bull.* 4, 1892; *U.S. Dept. Agric., Farmers' Bull.* 257, 1906.
[5] *U.S. Dept. Agric. Bur. Soils, Bull.* 22, 1903.
[6] *Jahrb. wiss. Bot.*, 1896, **29**, 321.
[7] *Jahrb. wiss. Bot.*, 1908, **46**, 55.

loss of potassium from the soil solution, hence the solid phase of the soil must be continually supplying potassium to make good the loss due to its uptake by the roots.

TABLE 102

Uptake of Potassium by Crops compared with the Depletion of Potassium in the Soil Solution[1]

Potassium in parts per million of soil

Number of soils used	K in soil solution			Depletion of K in soil solution	Uptake of K by crop
	Before crop sown		After crop harvested		
	Range	Mean	Mean		
14	5–10	8	8	0	104
27	10–15	12	8	4	87
40	15–20	17	12	6	116
29	20–25	22	11	12	133
17	40–45	41	14	28	161
24	45–55	50	16	34	246

A second explanation developed by Jenny and Overstreet[2] of this result is, however, possible. The plant root may be able to obtain exchangeable potassium and calcium directly from the solid particles of the soil, by excreting hydrogen ions from its surface which replace some of the adsorbed cations on the clay, a process Jenny and Overstreet called "contact exchange". These hydrogen ions come in part from the carbonic acid liberated by the roots during respiration, and in part by diffusion through the cell membrane, as in Lundegårdh's theory of nutrient uptake already discussed on p. 433, but they may also come from the organic acids[3] the roots synthesise to neutralise the excess of adsorbed cations[4] over anions. Further, Jenny and Overstreet[5] claim that cations can move fairly readily both over the surface of a clay particle, and also from one clay particle to another, provided their double layers interpenetrate. Hence, roots can draw on a considerable area of contiguous clay surfaces for their ions—they do not need to restrict themselves to the exchangeable ions in their immediate neighbourhood; and, in fact, W. A. Albrecht[6] and his co-workers showed

[1] G. S. Fraps, *Texas Agric. Expt. Sta., Bull.* 391, 1929.

[2] *Soil Sci.*, 1939, **47**, 257; *Proc. Soil Sci. Soc. Amer.*, 1940, **4**, 125. For a review of the subject, see D. I. Arnon, *Ann. Rev. Biochem.*, 1943, **12**, 499.

[3] *Amer. J. Bot.*, 1942, **29**, 227. [4] A. Ulrich, *Amer. J. Bot.*, 1941, **28**, 526; 1942, **29**, 220.

[5] *J. Phys. Chem.*, 1939, **43**, 1185. [6] *Amer. J. Bot.*, 1942, **29**, 210.

that if contact exchange is the sole means by which a plant growing in the soil obtains its cations, then surface migration must be important. This picture of contact exchange is obviously suited to describe the mode of uptake of nutrients, both anions and cations, when the root system contains many root hairs which have fine soil particles embedded in their surface (see p. 421), or when the anions and cations are both present as exchangeable ions on a mixed anion- and cation-exchange system.[1]

The process of contact exchange does not in fact differ fundamentally from uptake from the solution, for in either case the ion can only be transferred through the water film surrounding the root, and the composition of the soil solution is controlled by the solid phase of the soil as well as by the uptake of nutrients by the crop. The thinner the water film between the surfaces of the root and the solid surface, the more appropriate is the concept of contact exchange. On the other hand, uptake from the soil solution does not mean that the cations must be evenly distributed throughout the solution before they can be taken up: they will, in any case, be more concentrated near the source of the exchangeable ions than farther away.

But the ions present in the soil solution and as exchangeable ions do not form the sole reservoir on which the plant can draw. This is obviously true for calcium, as calcium carbonate is a reservoir of calcium ions. It is also true for potassium, as will be shown in Table 108 on p. 463. Here there must either be a continuous slow transfer of potassium from the non-exchangeable to the exchangeable form, or plant roots must be able to use non-exchangeable potassium by some process not yet discussed, an assumption that need not yet be made.

There is, however, some evidence that plant roots can use cations normally unavailable to them if the soil contains an acid clay. E. R. Graham[2] showed that an acid clay, particularly if it is rich in montmorillonite, is a powerful extractor of cations from mineral particles in the silt range, and he further showed[3] that this acid clay could act as a carrier of calcium from the mineral to the crop. Thus, he found that soybeans could take up more calcium, and make better growth, if they were growing in a mixture of quartz sand, finely ground anorthite and acid bentonite, than if they were growing in the sand and anorthite alone. The soybeans took up 16 mgm. of calcium if grown in the sand alone, 43 mgm. from the sand and anorthite, and 112 mgm. from the sand-anorthite and acid bentonite.

The soil solution in most fertile agricultural soils is an adequate source of supply for the phosphate requirements of the plant. The phosphate content of the solution is low, only 0·5 to 2 parts per million

[1] For examples of plants grown on such substrates, see F. S. Schlenker, *Soil Sci.*, 1942, **54**, 247; H. Jenny, *J. Colloid. Sci.*, 1946, **1**, 33.

[2] *Soil Sci.*, 1940, **49**, 277. [3] *Soil Sci.*, 1941, **51**, 65; *Amer. J. Bot.*, 1942, **29**, 210.

of PO_4, but since it remains remarkably constant at this value during the growing season, the solid particles are obviously releasing phosphates into the solution as rapidly as the crop is extracting them. But in soils low in available phosphate the plant roots must possess some means of bringing phosphates into solution, for crops differ considerably in their power of extracting phosphates from difficultly available forms. Their roots increase the soil acidity around their absorbing surfaces, due to the CO_2 they respire, but some roots, such as young lupins, can also excrete organic acids.

Transfer of Nutrients from the Root to the Soil

We have so far been discussing the transfer of nutrients from the soil to the root as if it were a one-way process. Yet roots can only hold their ions against diffusion into the soil if the aeration conditions are adequate, and cereals and tobacco excrete at least potassium into the soil towards the end of the growing season, as was discussed on p. 29 and shown in Table 4. Recent analytical work, particularly with radioactive tracer elements, has shown that there is, in fact, a continuous exchange between the nutrient ions in the soil and in the root, though the factors controlling this exchange are unknown. R. Overstreet[1] showed that barley roots put into distilled water or into a sodium chloride solution lost no potassium to either; they lost a little to a calcium chloride solution, but there was a large exchange of potassium from the root to the solution if the roots were in a potassium chloride solution. On the other hand, plant roots lose potassium rapidly if growing in sodium saturated clays, more slowly if in potassium, and still more slowly if in calcium saturated clays. E. I. Ratner[2] and W. T. McGeorge[3] also found that soils high in exchangeable sodium were able to extract calcium from the plant, and that if the plant had some of its roots growing in a calcium soil and some in a sodium, there was a transfer of calcium through the root system from the high calcium to the high sodium areas, though the experiments did not show if the quantities involved were large enough to have any practical significance. Soils can apparently also remove anions as well as cations from plants, for W. A. Albrecht[4] found that soybeans lost some of their phosphates when growing in calcium-deficient soils.

The Need for Fertiliser Placement

Plants can only obtain their main supply of nutrients from damp soil. Hence, it they are to use, during periods of drought, nutrients

[1] *Soil Sci.*, 1939, **47**, 257; **48**, 9. See also E. I. Ratner, *C.R. Acad. Sci.* (*U.S.S.R.*), 1944, **42**, 313; **43**, 126.
[2] *C.R. Acad. Sci.* (*U.S.S.R.*), 1945, **48**, 63; *Pedology*, 1944, Nos. 4–5, 205.
[3] *Arizona Agric. Expt. Sta., Tech. Bull.* 94, 1942. [4] *Proc. Soil Sci. Soc. Amer.*, 1940, **5**, 8.

added to the soil as fertiliser, the mobility of these nutrients in the soil is of great importance. Fertilisers are commonly put in the seed-bed and incorporated with all, or part, of the top few inches of the soil. Of the fertilisers added, only nitrates and chlorides are readily mobile in the soil: they wash down with the percolating water, usually accompanied by an equivalent amount of calcium ions. Potassium is also freely mobile in sandy soils low in organic matter, as they contain no base exchange material capable of holding it. But in land with an appreciable clay content, potassium moves down very slowly if the land is cropped, and only a little faster if it is left fallow, unless such large dressings are given that the surface soil is almost saturated with it,[1] for if the exchange complex in the surface soil has only a small proportion of potassium compared to other exchangeable ions, it will hold additional potassium ions fairly tightly. Phosphates and calcium carbonate as a neutralising agent move very slowly in the soil. Thus, Rice Williams[2] found that adding basic slag to a pasture for fifteen years barely affected the phosphate content of the soil below 3 inches, and B. W. Doak[3] found little movement below 6 inches after adding phosphate to a pasture for eight years. However, O. E. Sell and L. C. Olson, working on a pasture on a sandy loam in Georgia,[4] found that dolomitic limestone affected the *p*H of the soil 6 to 8 inches below the surface five years after the first application, and at 8 to 12 inches after nine years, though little calcium itself had actually moved below 4 inches at this time. They also found that 35 lb. per acre of P, given as a 35 per cent superphosphate in 1936 and again in 1939, increased the available phosphates at the 4- to 8-inch depth in 1944, whilst two dressings, each of 70 lb., increased the available phosphate in the 8- to 12-inch layer at this time. However, if nitrogen and potassium were added with the phosphate so that growth of the pasture was stimulated, penetration of the phosphate was considerably reduced, little penetrating below 6 inches. The cause of the discrepancies found in the literature is probably that the phosphate of calcium monophosphate is more mobile in neutral or in limed acid soils than in unlimed acid soils.[5]

Nutrients supplied in fertilisers do not move laterally appreciably in level fields. Thus a grass field at Rothamsted, originally uniform in its herbage, was in 1856 divided into plots, each of which actually

[1] W. H. MacIntire *et al.*, *Soil Sci.*, 1943, **55**, 321.

[2] *Welsh J. Agric.*, 19, **16**, 132.

[3] *New Zealand J. Sci. Tech.*, 1942, **24** A, 141, and 1933, **15**, 155, for a bibliography to earlier work. See also M. Odelien and T. Vidme, *Meld. Norg. Landbr.*, 1945, **25**, 273, for other experiments showing the immobility of potassium and phosphates in soils.

[4] *Proc. Soil Sci. Soc. Amer.*, 1947, **11**, 238; for other American work on this, see L. C. Olson, ibid., 1946, **10**, 443; A. R. Midgley, *J. Amer. Soc. Agron.*, 1931, **23**, 788; P. R. Nelson, *Soil Sci.*, 1929, **27**, 143.

[5] W. H. MacIntire *et al.*, *Proc. Soil Sci. Soc. Amer.*, 1948, **12**, 359.

touches its neighbours; certain manurial treatments have been given annually to each and continued without change ever since. Marked differences in herbage have resulted, but the edges bounding the plots are fairly sharp; there is no evidence of much lateral diffusion in the period of ninety years.

Phosphates, potassium and calcium carbonate do not, therefore, naturally move easily in a soil, and if one wants to enrich the subsoil in any of these three materials, one should work them into the subsoil direct. This is very necessary for calcium carbonate if the subsoil is acid, for only in this way can the root system of most crops penetrate to a reasonable depth. Experimental evidence is still somewhat incomplete, but it is probably always desirable to plough in lime as deeply as possible if the subsoil is very acid and drought during the growing season probable, for only by neutralising this acidity can the plant roots penetrate into the subsoil and so be able to extract much water from it. It is further probable that at least part of the potassic and phosphatic fertilisers, and in some climates the nitrogen also, should be incorporated with the subsoil in areas subject to summer drought and where the subsoils are poor and the crop needs a good supply of nutrients throughout the summer. Thus, E. W. Russell has found that, in dry summers in England, sugar-beet responds better to potassium and phosphate mixed with the top 9 inches of soil than the top 2–3 inches, but that wheat and barley do not show this benefit; and D. D. Smith *et al.*,[1] working on a clay pan soil in Central Missouri, found that maize benefited by deep incorporation of fertilisers but oats and barley did not, for as already stated the small grains take up the bulk of their potassium and phosphate before summer drought has dried out the subsurface soil.

A need for fertiliser placement can arise from another cause besides that for keeping nutrients in damp soil within the root zone for as long as possible. If a soil is very poorly supplied with a particular nutrient, then the crop appears to be able to take up more of this nutrient from a dressing of fertiliser concentrated in the soil near the plant, than if the same dressing is broadcast over the surface of the soil. This has been shown to be true for potassic and phosphatic fertilisers. The causes of this benefit of fertiliser placement have not been analysed. Part may be due to the fact that when the fertiliser is placed, it is all kept below the soil surface so that none will be in the actual surface layer of the soil. Part may be due to the fact that the plants showing greatest benefit from this placement probably take up the potassium and phosphate

[1] *Agric. Engng.*, 1947, **28**, 347; *Proc. Soil Sci. Soc. Amer.*, 1947, **11**, 539; for confirmatory data for maize only, see J. Pitner (*Proc. Natl. Joint. Cttee. Fert. Appl.*, 1944, **20**, 138), who found the yield of maize was increased 20 to 25 per cent by placing the fertiliser 8 to 10 inches below the seed instead of 2 to 3.

they need for good growth early on in the season, before the plant has developed an extensive root system. For potassium on calcareous soils, part may be due to the plant being able to take up potassium easier from a zone containing a high ratio of available potassium to calcium than a low. For phosphatic fertilisers, part may be due to the slower reversion of available phosphate when concentrated in a restricted zone of the soil than when distributed uniformly throughout the soil; and for soils that fix phosphate strongly, it may even be worth while placing pellets of a phosphatic fertiliser under each plant.

The technique of fertiliser placement for cereals is to drill the fertiliser and the seed down the same coulter of the drill. This technique has been extensively used on the phosphate-deficient wheat soils of Australia, where as little as $\frac{1}{2}$ cwt. of superphosphate per acre so drilled enables a crop to grow well in its early stages. It also started to be widely practised in Great Britain during the war on phosphate- and also on potassium-deficient land, for it is only necessary to combine-drill half the dressing of a phosphatic or potassic fertiliser that must be given if it is broadcast, to get a given crop response.[1] There is a second technique of fertiliser placement, that has been widely advocated in America, which is to drill the fertiliser in a band a few inches away from the seed—2 inches to the side and 2 inches below the level of the seed being a common recommendation. G. W. Cooke[2] has tested the value of this technique in England and was only able to show an appreciable benefit for peas; the other crops he tried—potatoes, sugar-beet and swedes—did not benefit by this technically rather difficult method of application. This beneficial effect of placement can be increased still further in some alkaline soils by mixing sulphur with the superphosphate, for the sulphur becomes oxidised and makes the soil and phosphate in its immediate neighbourhood more acid, thus keeping the phosphate in an available form for a longer period.[3]

[1] A. H. Lewis, *J. Agric. Sci.*, 1941, **31**, 295; with A. G. Strickland, ibid., 1944, **34**, 73; E. M. Crowther, *J. Min. Agric.*, 1945, **52**, 170; F. Hanley, *J. Min. Agric.*, 1947, **54**, 354; R. O. Miles, *Jealott's Hill Res. Sta., Bull.* 4, 1947.

[2] *J. Agric. Sci.*, 1949, **39**, 96; *Proc. Fertiliser Soc.*, 1949, No. 6.

[3] W. T. McGeorge, *Proc. Soil Sci. Soc. Amer.*, 1940, **4**, 288.

CHAPTER XXVI

THE SOURCES OF PLANT NUTRIENTS IN THE SOIL

The Phosphorus Compounds

FOUR GROUPS OF phosphorus compounds have been proved to exist in the soil,[1] in all of which the phosphorus is present as PO_4:

1. Inorganic minerals containing phosphates as an integral part of their structure. Apatites $Ca(OH)_2\,3Ca_3(PO_4)_2$, and fluor-apatites, in which fluoride replaces hydroxyl, are the most widespread, but iron phosphates also occur under some conditions.

2. Insoluble calcium phosphates produced when soluble phosphates are added to the soil. It is still uncertain what these compounds are. Dicalcium phosphate $CaH(PO_4)$ almost certainly occurs, the tricalcium phosphate $Ca_3(PO_4)_2$ almost certainly does not; and a compound of composition $Ca_4H(PO_4)_3$, which R. Warington[2] called an octaphosphate, may also be present and be the intermediate compound through which the dicalcium phosphate becomes converted back to an apatite.

3. Phosphates held on the surface of hydrated iron and possibly aluminium oxides. There is no sharp distinction between this group and the iron and aluminium phosphate minerals, for under some conditions these complexes probably crystallise to form new minerals. Phosphates may also be held on the surface of clay particles by mechanisms other than these hydrated oxides.

4. Organic phosphates, such as phytin and other inositol phosphates, nucleic acid and its derivatives, and the other compounds that make up the humic material, the partially decomposed plant tissues and the tissues of the living plant roots and the soil population. Typically the organic phosphorus content of a soil varies from 2 to $\frac{1}{2}$ per cent of the organic carbon (see p. 273).

The phosphate problems of primary agricultural importance concern the availability of these different forms to the plant root, and the reactions that take place when phosphates are added to a soil, for it was very early discovered that water-soluble phosphates added to a soil are rapidly converted into insoluble forms, and that only a small

[1] Methods for fractionating the various phosphates present in soils have been suggested by L. A. Dean, *J. Agric. Sci.*, 1938, **28**, 234, and M. O. Ghani and S. A. Aleem, *Indian J. Agric. Sci.*, 1943, **13**, 142, 283.

[2] *J. Chem. Soc.*, 1866, **19**, 296; 1873, **26**, 983.

proportion of the added phosphate is taken up by the crop, the rest being apparently converted into useless or almost useless forms.

It is probable, as discussed on p. 38, that the only inorganic form of phosphate plants can take up is the $H_2PO_4^-$, and if this is correct the value of a phosphatic mineral as a source of phosphate to the crop depends on the concentration of $H_2PO_4^-$ ions it can maintain in the soil solution and on the power of the plant roots to extract these ions from it.

Plant roots can directly take up certain organic phosphates such as phytin and other inositol phosphates, and there are suitable enzymes on the surface of their roots to dephosphorylate nucleic acid and its derivatives.[1] But it is unlikely plants take up these organic phosphates from the soil, for these are more probably dephosphorylated by the general microbial population and the roots only take up the orthophosphate anions thus set free. There also appear to be water-soluble organic phosphorus compounds of unknown composition that are not taken up by the plant,[2] though H. J. Atkinson and his co-workers[3] found that the organic phosphorus compounds that readily disperse in water after sodium chloride has been percolated through the soil are readily available, but again their composition is not known. There can also be competition between the plant and the soil micro-organisms for phosphates, and if a large dressing of a readily-decomposable organic manure low in phosphates is added to a phosphate-poor soil, the crop may suffer from severe phosphate starvation[4] in a manner exactly analagous to the nitrogen starvation that can be induced by such a method.

The hypothesis that $H_2PO_4^-$ ions are normally the sole source of phosphate for the plant has several consequences. In the first place phosphate uptake would be confined to soils that are not too alkaline, for the proportion of $H_2PO_4^-$ ions to HPO_4^{--} ions in solution as the *p*H changes from 4 to 9 is given in Table 103. The PO_4^{---} ion concentration is too low to be of any significance.

Thus, once the *p*H outside the plant root is in the neighbourhood of 8 one can expect the plant to suffer from phosphate starvation. It is, of course, important to remember that the *p*H concerned is not necessarily that of the soil as measured by most present day techniques, as these usually give a *p*H in excess, and sometimes considerably in excess of the effective *p*H in the neighbourhood of the root, as explained in Chapter 7.

[1] H. T. Rogers, *Proc. Soil Sci. Soc. Amer.*, 1940, **5**, 285; *Soil Sci.*, 1942, **54**, 499; B. R. Bertramson and R. E. Stephenson, *Soil Sci.*, 1942, **53**, 215; V. E. Spencer and F. M. Willhite, *Soil Sci.*, 1944, **58**, 151.

[2] H. T. Rogers, *Soil Sci.*, 1942, **54**, 499; A. Kaila, *Valt. Maatalousk. Julk.*, 129, 1948.

[3] *Soil Sci.*, 1944, **58**, 79.

[4] D. Chouchak, *C.R.*, 1927, **185**, 82; 1929, **189**, 262.

TABLE 103

The Proportion of Phosphate Ions in Solution per 100 Mols of Dissolved Phosphate[1]

pH	4	5	6	7	8	9
Mols of H_3PO_4	0·9	0·1	8×10^{-3}	3×10^{-4}	4×10^{-6}	5×10^{-8}
Mols of $H_2PO_4^-$	98·9	98	82	33	3	0·5
Mols of HPO_4^{--}	0·2	2	18	67	97	99·5
Mols of PO_4^{---}	7×10^{-10}	7×10^{-8}	6×10^{-6}	2×10^{-4}	3×10^{-3}	4×10^{-2}

In the second place the ability of calcium phosphates to supply phosphate ions would be expected to increase with increasing acidity. As will be discussed on p. 457, our knowledge of the chemistry of the calcium phosphates is very limited, although such knowledge is fundamental for any accurate discussion of soil phosphates. Here it is sufficient to remark that monocalcium phosphate, $Ca(H_2PO_4)_2$ the phosphatic component in superphosphate, is water soluble,[2] but when added to soil containing exchangeable calcium ions it becomes converted to the insoluble dicalcium phosphate $CaHPO_4$ and may be formed on the surface of the clay particles. But this phosphate is sufficiently soluble to maintain a concentration of HPO_4^{--} ions in solution high enough to allow an adequate proportion of $H_2PO_4^-$ ions to be present, for the ratio of these two ions present in the soil solution is as given in Table 103 above. Thus, although dicalcium phosphate is water insoluble for most practical purposes, yet it is soluble enough to maintain an adequate supply of $H_2PO_4^-$ ions, particularly in acid solutions. But the dicalcium phosphate itself becomes converted to still more insoluble phosphates, which maintain a still lower HPO_4^{--} or PO_4^{---} ion concentration so that it is only under acid conditions that the $H_2PO_4^-$ ion concentration, corresponding to the concentrations of these other ions, is high enough for good plant growth.

Phosphate fertilisers have, however, only a limited availability in acid soils for another reason. Acid soils contain reactive forms of aluminium, and often of iron also, which combine with the $H_2PO_4^-$ ions in solution to give aluminium and iron phosphates; some of these, particularly if they have been dehydrated, are so insoluble that they only maintain in solution a concentration of $H_2PO_4^-$ ions quite inadequate for crop growth.[3] Thus, this particular form of reversion goes

[1] Computed from T. F. Buehrer, *Arizona Agric. Exp. Sta., Tech. Bull.* 42, 1932.

[2] G. H. Collings (*Commercial Fertilisers*, 4th ed., New York, 1947), quotes the solubilities of these calcium phosphates in water at 15° C. in grams per 100 c.c. of solution as follows: $Ca(H_2PO_4)_2.H_2O$, 4·0; $CaHPO_4.H_2O$, 0·028; $Ca_3(PO_4)_2$, 0·0013.

[3] For a pot experiment illustrating this, see J. F. Poulsen, *Tidskr. Planteavl*, 1948, **51**, 616.

on most rapidly in hot tropical climates having a pronounced dry season, and since many of the soils in such climates are both acid and very well supplied with these reactive aluminium and iron compounds, this particular form of phosphate fixation is very serious.

There are no known ways of altering the soil conditions so these iron and aluminium phosphates can be made available to the crop. In practice in temperate agriculture, the soil is limed before the phosphate is applied so the acidity, and hence the concentration of these reactive iron and aluminium ions, is reduced. Liming an acid soil often increases the amount of available phosphate, but this phosphate is probably derived from the organic matter present—for liming increases its rate of decomposition. On tropical and sub-tropical acid soils heavy liming is rarely feasible, nor is it known if it is desirable, hence the problem of making efficient use of phosphate fertilisers on such soils may have to be solved by other methods. These include the band placement of a phosphate fertiliser near to the plant, possibly preferably as a granular fertiliser, and possibly again as a water-insoluble fertiliser such as the dicalcium phosphate. They also include the use of superphosphate protected from the iron and aluminium ions by mixing it with farmyard manure or compost, and the use of ground rock phosphate, although this may have to be made available to some crops by giving it to a green manure crop which is able to extract phosphate from it, and then ploughing it in.

The surface of clay particles, and of some minerals such as mica,[1] will adsorb phosphates. Under acid conditions this adsorption is brought about in part by the aluminium ions that neutralise the negative charge on the clay particle, as described on p. 114, and hence is the same mechanism as has just been discussed. The two relevant problems here are whether clay minerals adsorb phosphate by any other mechanism and how available is this adsorbed phosphate to the plant. In a later paragraph another mechanism by which clays can hold phosphate, namely, through the exchangeable calcium and magnesium ions on their surface, will be discussed. It is still not known for certain if clay minerals can adsorb phosphates by still other mechanisms, as, for example, by the phosphate replacing some of the hydroxyl ions on the outside of the kaolinite sheets, but present evidence indicates that it is unlikely.[2]

Much of this adsorbed phosphate acts as a replaceable anion on the clay surface, and as already discussed on p. 116, it can be displaced by other anions, whose replacing power usually increases with basicity.

[1] A. T. Perkins and H. H. King, *Proc. Soil Sci. Soc. Amer.*, 1944, **8**, 154.

[2] See, for example, P. F. Low and C. A. Black, *Proc. Soil Sci. Soc. Amer.*, 1948, **12**, 180, for the kind of evidence available.

Thus, T. Kurtz, E. E. De Turk and R. H. Bray[1] found that, of the anions they used, the chloride, sulphate, and acetate were weak replacers of this phosphate, bicarbonate and citrate were more powerful, and oxalate and fluoride (although only monobasic) the most powerful. Silicate is also known to be a strong replacer, and it is probably through this action that it causes the plant to take up extra phosphate (see p. 45) when it is added, as sodium silicate, to a soil low in phosphate.

However, it is still uncertain where the phosphate is held that is replaced by these anions. It is possible that it is combined with hydrated iron and aluminium ions to give a salt of the form $Al(H_2O)_3(OH)_2.H_2PO_4$, and that anions such as citrate, oxalate and flouride can readily displace the phosphate from this salt to give more stable co-ordination compounds, but that they lose this power as the iron or aluminium phosphate becomes less hydrated.[2]

It is possible, but still unproven, that the reactive iron and aluminium compounds are responsible for all the phosphate adsorption that occurs in acid soils containing no exchangeable calcium ions, for their phosphate adsorbing power is greatly reduced if the iron and aluminium compounds readily soluble in Truog's hydrogen sulphide treatment are removed;[3] and the evidence so far available is not inconsistent with the view that it would be almost completely removed if the soil had a sufficiently thorough treatment with Tamm's acid oxalate solution (see p. 114).

Calcium clays can also adsorb water-soluble phosphates by the phosphate being converted to the relatively insoluble dicalcium phosphate on their surfaces. Thus, they adsorb more phosphate from a phosphate solution than sodium or potassium clays,[4] and several workers have suggested that this is due to half the positive charge on each calcium ion neutralising part of the negative charge on the clay and the other half combining with a phosphate anion. But there is no need to postulate this mechanism—it is much more likely that the insoluble dicalcium phosphate is formed on the clay surface.

THE PHOSPHATIC FERTILISERS

The principal primary source of phosphate for fertilisers is rock phosphate, which is mined in North Africa, Florida, Nauru and elsewhere, and these minerals contain fluor-apatite and perhaps other apatites as well. The principal phosphatic fertiliser of commerce is superphosphate,

[1] *Soil Sci.*, 1946, **61**, 111. See also L. A. Dean and E. J. Rubins, *Soil Sci.*, 1947, **63**, 377.
[2] R. M. Swenson *et al.*, *Soil Sci.*, 1949, **67**, 3.
[3] W. H. Metzger, *J. Amer. Soc. Agron.*, 1940, **32**, 513; 1941, **33**, 1093; J. B. Kelly and A. R. Midgley, *Soil Sci.*, 1943, **55**, 167; R. Coleman, *Soil Sci.*, 1944, **58**, 71; *Proc. Soil Sci. Soc. Amer.*, 1944, **9**, 72.
[4] See, for example, L. E. Allison, *Soil Sci.*, 1943, **55**, 333; G. Barbier *et al.*, *Ann. Agron.* 1946, **16**, 8.

which is made by treating rock phosphate with sulphuric acid to break down the apatite structure producing monocalcium phosphate. This breaking down of the apatite structure is necessary because rock phosphate is of no use as a phosphatic fertiliser on many soils.

Numerous experiments have, however, shown that finely ground rock phosphate is as effective as superphosphate on acid soils in cool moist climates for a number of crops such as pastures, oats, swedes and turnips.[1] Hence, under these moist acid conditions it presumably slowly releases phosphate ions; but since some crops, such as potatoes for example, respond much less well to it, the plant roots, or their rhizosphere population,[2] may play an active part in helping to extract these ions. Thus, R. L. Cook[3] has shown that the demands of the crop for calcium helps to determine its power of using this phosphate. He found buckwheat, with a high calcium demand, was a more efficient user of rock phosphate than oats, maize and millet—all plants with a low calcium demand—though the potato, which probably has a higher calcium demand than oats, appears to be a poorer extractor of phosphate. Cook also showed that plants could take phosphate more easily from rock phosphate if an acid clay (he used acid bentonite) was present.

There are other methods available besides using sulphuric acid for breaking down the apatite structure of rock phosphate, though so far they have been little used. But these other methods, although not using sulphuric acid, require a large supply of energy, either as a solid fuel or as electric power. The rock can, for example, be treated with phosphoric instead of sulphuric acid, the phosphoric acid being made from phosphorus derived from the rock. This product is known as triple superphosphate, because it has three times the phosphorus content of ordinary superphosphate as it contains no calcium sulphate and only a little calcium fluoride. Again, the rock can be treated at high temperature with steam or alkali and silica to give either a tricalcium phosphate $Ca_3(PO_4)_2$ or a silico-phosphate, or the metaphosphate $Ca(PO_3)_2$. This latter theoretically contains 31 per cent of phosphorus, actually 29–30 per cent, so is the most concentrated phosphatic fertiliser made, but when added to the soil it hydrolyses to the orthophosphate. These phosphates are as good as superphosphates on acid or mildly acid soils, but are probably less effective on neutral to alkaline soils, particularly for crops such as potatoes,[4] and particularly in dry seasons.

[1] For some typical experiments, see E. J. Russell, *Min. Agric., Bull.* 28, 3rd ed., 1939.
[2] F. C. Gerretsen, *Plant and Soil*, 1948, **1**, 51.
[3] *J. Amer. Soc. Agron.*, 1935, **27**, 297.
[4] For British results and processes, see E. M. Crowther and F. M. Lea, *J. Min. Agric.*, 1946, **53**, 102; E. G. Williams and J. W. S. Reith, *Emp. J. Exp. Agric.*, 1948, **16**, 1. For American data, see H. A. Curtis *et al.*, *Ind. Engng. Chem.*, 1937, **29**, 766; K. D. Jacobs and W. H. Ross, *J. Agric. Res.*, 1940, **61**, 539; B. E. Brown and K. G. Clark, *Amer. Fert.*, 1943, **98**, No. 5, 10; W. H. MacIntire *et al.*, *Soil Sci.*, 1944, **57**, 425.

Another group of phosphatic fertilisers are the basic slags, which are by-products in the manufacture of steel. Several types of phosphate compounds occur, but only some are of any value as phosphate fertilisers. It has been found empirically that their value can be assessed by the proportion of their phosphate that dissolves in 2 per cent citric acid.

THE REVERSION OF PHOSPHATE FERTILISERS IN THE SOIL

Phosphate fertilisers differ from nitrogen, potassium and calcium fertilisers in that only a relatively small proportion of the applied phosphate is taken up by the crop. In normal British farming practice, it is unlikely that more than 10 per cent is recovered in the crop to which the fertiliser is given and a further 10 per cent in the succeeding crops. However, as some experiments of E. M. Crowther and G. W. Cooke show, on very phosphate-deficient soils, one can have higher uptakes than this in the year of application. Table 104[1] shows that under these

TABLE 104

Uptake of Added Phosphate by Swedes on Phosphate-deficient Soils

Mean of 27 experiments, 1942
Phosphorus added as superphosphate

P added in fertiliser, cwt. per acre	Yield of roots in tons per acre	Increase in yield due to each increment of phosphate	P in roots, cwt. per acre	Uptake of P from each increment	
				in cwt. per acre	as per cent of P added
0	6·1	—	0·025	—	—
0·22	15·4	9·3	0·060	0·035	16
0·44	17·2	1·8	0·080	0·020	9

very favourable conditions, swedes can take up 16 per cent of a dressing of 3 cwt. per acre of superphosphate, a dressing which increases their yield two-and-a-half-fold; but doubling this dressing of fertiliser had little effect on yield though 9 per cent of the phosphate it supplied was taken up. Presumably if a still lower rate of phosphate application had been made, a still higher proportional uptake would have been found.

The residual effect of added phosphate can be seen from some grassland hay experiments made at seven centres over England between 1930 and 1935. The relevant results are given in Table 105. It shows that the effect of the phosphate was nearly exhausted four years after it had been added, though only between 15 and 30 per cent had been recovered, and the proportion recovered was not very dependent on

[1] I am indebted to Drs. Crowther and Cooke for permission to use this unpublished table.

the increase of hay yield brought about by the phosphate. The high recovery of 30 per cent was confined to fields mown for young grass. In these experiments mineral phosphate, when it was effective, and high soluble slags had the same residual effect as superphosphate.

TABLE 105

Uptake of Phosphate by Hay and Grass in Successive Years after Phosphate Manuring[1]

Per cent of added P recovered in Hay or Mowings

0·44 cwt. P per acre added as superphosphate

Year	2 neutral soils[2]	3 acid soils[3]	2 soils, grass mown[4]
Application	7·7	8·3	13·7
1 year after	5·7	5·0	9·4
2 years after	1·8	3·3	5·8
3 years after	1·5	2·3	2·1
Total recovery	16·7	18·9	31·0

However, there are some experimental results which indicate that superphosphate may have a more lasting effect that this. In a four course rotation experiment at Rothamsted[5] (potatoes—barley—seeds—wheat), for example, 0·5 cwt. per acre of P, as superphosphate, given to the potato crop increased its yield by 2·2 tons per acre; but it increased its yield by 1·1 tons per acre if given to the land in any one of the four preceding years. In the same way the phosphate, given to the barley crop, increased its yield by about 5 cwt. per acre, and by about 2 cwt. per acre if given to any one of the four preceding crops; and it increased the yield of rye grass hay by 2 cwt. per acre of dry matter if given to the rye grass or to any of the four preceding crops. And these results are based on a well-designed experiment that had been running for twelve years. Again, G. W. Volk,[6] working on a loam soil in Alabama, found that cotton was responding to five annual dressings of superphosphate ten years after the last application had been given, and the response after ten years was larger, the larger the amount of phosphate that had been given. Unfortunately, in neither of these experiments have the phosphate uptakes been determined, so it is not known why these

[1] Figures taken from E. J. Russell, *Min. Agric. Bull.* 28, 3rd ed., 1939, and from the *Basic Slag Reports to Min. Agric.*, 1933 and 1934.
[2] Braintree, and Badminton, Glos.
[3] Northallerton, Chesterfield, and Lydbury, Salop.
[4] Dartington Hall, Totnes (acid) and Much Hadham, Herts (neutral).
[5] E. M. Crowther, *J. Roy. Agric. Soc. England*, 1946, **107**, 107.
[6] *J. Amer. Soc. Agron.*, 1945, **37**, 330.

results appear to differ from the ones discussed in the preceding paragraph.

The reason for the low uptake of phosphate is that it becomes converted into forms much less soluble than dicalcium phosphate, and this conversion has usually been completed after the phosphate has been in the soil for 2–3 years. In acid soils the phosphate is presumably locked up as aluminium and iron phosphates, which, as has already been mentioned, are of little value as sources of phosphate, particularly after they have been dried.

In neutral soils the dicalcium phosphate appears to react with more calcium, giving perhaps first a compound of the octaphosphate type $Ca_4H(PO_4)_3$ before reverting to an apatite $CaX_2.3Ca_3(PO_4)_2$, (when X=OH or F). It does not appear to revert to the triphosphate $Ca_3(PO_4)_2$. The main problems that have not yet received a definitive answer are whether the apatites formed are all equally available to the crop and whether there is anything one can do to reduce the speed with which this reversion takes place.

W. H. MacIntire[1] has developed the thesis that fluor-apatite is less available to the plant than hydroxy-apatite, and hence has advocated the use of fluorine-free phosphatic fertilisers. Phosphatic fertilisers made from rock phosphate, which is a fluor-apatite, must contain enough calcium fluoride to convert the dicalcium phosphate back again to fluor-apatite unless the fluorine has been removed during the process of manufacture, for calcium fluoride washes out of the soil very slowly.[2] But there appears to be no reliable body of field experimental data to show that fluoride-free phosphatic fertilisers revert more slowly than superphosphate to the useless forms.

Claims have also been made that the water-insoluble dicalcium phosphate reverts more slowly than the monophosphate on the theoretical grounds that the monophosphate will be precipitated as a very thin film of diphosphate over the clay particles, hence will have a far larger exposed surface than dicalcium phosphate added directly to the soil.

The practice of applying phosphatic fertilisers as the insoluble diphosphate rather than as the soluble monophosphate is, however, rapidly spreading. In New Zealand during the war much use was made of a serpentine superphosphate, made by mixing the magnesium silicate mineral serpentine with superphosphate, to give a water-insoluble calcium-magnesium phosphate.[3] Again if superphosphate absorbs ammonia, a mixture of ammonium and calcium phosphates are

[1] See, for example, *Indust. Engng. Chem.*, 1937, **29**, 758; *Soil Sci.*, 1942, **53**, 43.
[2] W. H. MacIntire *et al.*, *Soil Sci.*, 1948, **65**, 321.
[3] For a summary of the value of serpentine superphosphate, see G. H. Holford, *New Zealand J. Agric.*, 1946, **73**, 289.

formed, much of which is insoluble. This happens when superphosphate is mixed with farmyard manure, a practice which can reduce the loss of ammonia from manure heaps if properly used. Superphosphate has a longer lasting effect on some acid soils if it is applied when so mixed with manure than by itself,[1] but it is not permissible to argue from this that the insoluble phosphate is preferable on such soils, although it may be. It could equally well be due to the water-soluble phosphate being adsorbed by the organic matter rather than by iron or aluminium hydroxides.[2] Again, at the present time in America, the practice of adding anhydrous ammonia to superphosphate to produce a fertiliser having between 3 and 4 per cent of nitrogen is increasing.[3] The phosphate in these ammoniated superphosphates is mainly water-insoluble but it is soluble in ammonium citrate,[4] and this is the test used to replace the water solubility test for ordinary superphosphates to judge their value as a fertiliser.

A correct evaluation of the facts of phosphate reversion in the soil is important when one discusses the most efficient way of using phosphatic fertilisers. If the general result that the main effect of the fertiliser is shown in the first year and its residual effect becomes rapidly less, no attempt should be made to build up the phosphate reserves in the soil, but rather just enough phosphate should be given in the most efficient way to each crop for it to make optimum growth. Thus, methods of fertiliser placement, with fairly coarsely granular phosphate where necessary, should be developed and used. As an example from this country, corn crops on phosphate-poor soils need twice as much phosphate if it is broadcast than if it is combine-drilled with the seed (p. 448). And these practices are even more essential if the soil is of a type that rapidly immobilises added phosphates. On the other hand, for normal reasonably fertile arable soils, if the phosphate-responsive crops are adequately manured, the residual value of the added phosphate will be adequate for several succeeding crops having a smaller phosphate requirement.

The conclusions that can be drawn from this discussion are that two mechanisms have been recognised which convert available phosphatic fertilisers into unavailable forms: the formation of iron and aluminium phosphates on acid soils and the formation of apatites on neutral and alkaline. Whether these are the only two mechanisms present is

[1] A. Aslander, *Kgl. Lantbr. Akad. Tidskr.*, 1940, **79**, 385; A. R. Midgley, *Vermont Agric. Exp. Sta., Bull.* 525, 1945.

[2] For an example, see R. Chaminade, *C.R. Conf. Pédol. Méditerr.*, 1948, 222.

[3] See J. D. S. Holmes, *Amer. Fert.*, 1941, **95**, No. 9, 7; R. M. Jones and L. V. Rohner, *J. Assoc. Off. Agric. Chem.*, 1942, **25**, 197; G. H. Collings, *Commercial Fertilisers*, 4th ed., New York, 1947.

[4] The particular solution used is to dissolve 370 gm. of crystallised citric acid in 1500 c.c. of water, neutralise with ammonia, and dilute to bring its specific gravity to 1.09 at 20° C. (*A.O.A.C., Methods of Analysis*, 1930.)

uncertain, but they fit in with the commonly expressed view that phosphatic fertilisers last longest on mildly acid soils.

THE LEVEL OF AVAILABLE PHOSPHATE IN THE SOIL

The problem of estimating the available phosphate in the soil, or the probability that a given crop will respond to a dressing of phosphate given to the soil, is complicated by there being at least two factors involved. One factor is the extensiveness of the root system and the depth to which it penetrates, i.e. the volume of soil from which the crop can extract phosphate. This volume depends on the rainfall and other factors influencing the depth of rooting. Since the extensiveness of the root system also depends on the phosphate status of the soil, adding moderate dressings of phosphate to a phosphate-poor soil may so increase the root system that it not only takes up much of the added phosphate but also takes up more of the soil phosphate as well,[1] as already discussed on p. 426. The other factor is the ability of the roots to use the less easily available phosphates. Very little is known about why crops differ in this respect, and even the ability of a given crop to use a rather unavailable form seems to depend on its phosphate nutrition, for the greater the supply of readily available phosphate, the less of the less readily available form will it take up,[2] though once again, this may be merely a reflection of the effect of phosphates on the extensiveness of the root system. One factor is that some crops excrete organic acids from their roots. Another is that crops have different concentrations of carbon dioxide outside their roots, due perhaps to the respiration of the rhizosphere and mycorrhizal micro-organisms and nodule bacteria; and the rhizosphere and mycorrhizal organisms may have a greater ability to use insoluble phosphates than the uninfected roots and may transfer some of the phosphate mobilised to the roots of the crop. The relative importance of these factors may depend on soil conditions, such as aeration, for example, unrelated to the form of the phosphate in the soil.

The principal methods for estimating the amount of available phosphate in the soil are to treat the soil with a suitable solvent, such as citric or acetic acid or ammonium fluoride, and to determine the amount of phosphate in the extract. Biological methods have also been used such as measuring the amount of phosphate rye seedlings[3] can take up, or the amount of growth phosphate-demanding bacteria, such as *Azotobacter*, or fungi, such as *Aspergillus*, can make under controlled conditions.

[1] J. W. T. Spinks *et al.*, *Sci. Agric.*, 1948, **28**, 79, 309 (using wheat); K. Strzemienski, *Nature*, 1948, **162**, 932 (using rye-grass).

[2] L. A. Dean *et al.*, *Proc. Soil Sci. Soc. Amer.*, 1948, **12**, 91.

[3] For Neubauer's method, see H. Neubauer and W. Schneider, *Ztschr. Pflanz. Düng.*, 1923, A **2**, 324.

All these methods give a good indication if a crop is likely to fail because of phosphate shortage, or if the soil is so well supplied with available phosphate that additional phosphate is unnecessary. But no single method can accurately grade soils in order of the responsiveness of the crop growing on them to additional phosphate because of the different abilities of crops to extract phosphate from the soil as already indicated. However, over a series of soils and seasons, such tests can give a good indication of the average response of a crop to phosphate. This is illustrated in Table 106,[1] which is the result of a large number of experiments made on different English sugar-beet soils over a period of 9 years.

TABLE 106

Response of Sugar-beet to Superphosphate on Soils with different contents of Citric-soluble Phosphate

English sugar-beet experiments made during 1936–46

Phosphate fertiliser, 6 cwt. per acre of superphosphate (0·44 cwt. per acre P)
1 per cent citric acid used as extractant—all soils contain less than 5 per cent $CaCo_3$

Citric soluble P in mgm. per 100 gm. soil	Number of fields	Response to phosphate Sugar in cwt. per acre
Below 8 . .	54	3·7
8–12 .	54	1·5
12–17 .	54	1·1
Over 17 . .	54	0·5

It shows the average response of sugar-beet, measured in hundredweights per acre of sugar, to a dressing of 6 cwt. per acre of superphosphate on a number of soils grouped according to the amount of phosphate extracted by 1 per cent citric acid that they contain. This was the first extractant to be used,[2] and still is as satisfactory as any on neutral soils, though it over-estimates the phosphate reserves in acid soils as it dissolves some unavailable iron phosphates. For such soil dilute acetic acid appears to be preferable.[3]

The crops which can obtain phosphates least readily from the soil are not necessarily those which are most sensitive to phosphate starvation nor those which respond best to additions of phosphatic fertilisers, as can be seen from the following table:

[1] E. M. Crowther, *Bath and West Agric. Soc., Pamph*, 13, 1948. For a similar result for responsiveness of Idaho crops to phosphate fertilisers on soils of different phosphate status, see V. T. Smith, *J. Amer. Soc. Agron.*, 1948, **40**, 1045.

[2] B. Dyer, *Trans. Chem. Soc.*, 1894, **65**, 115; *Phil. Trans.*, 1901, **194** B, 235.

[3] I am indebted to R. G. Warren for this statement.

	Ability to obtain phosphorus from relatively insoluble phosphates	Responsiveness to further additions of phosphate	Sensitiveness to phosphate starvation
Most	Lupins, lucerne, sweet clover	Potatoes	Swedes and turnips
	Swedes, turnips, mustard	Swedes and turnips	Potatoes
	Buckwheat, millet	Mangolds	
		Barley	Oats
		Hay	
Least	Oats, wheat, barley	Oats and wheat	Hay
	Potatoes, maize, cotton		

The fact that some crops have a considerably greater power than others of using the less readily available sources of phosphate opens up the possibility of making them convert some of these phosphates into a more easily available form by growing them as a green manure crop and ploughing them in whilst their leaves and stems are still fairly succulent and readily decomposable. Thus lupins, which are one of the strongest extractors of phosphate among farm crops, have been extensively used as a green manure crop in Northern Europe for this purpose. Further, lupins can make soil phosphates more easily available by another mechanism. They appear to bring some of the less readily available phosphates into solution by excreting an organic acid from their roots:[1] this dissolving action is so strong that the roots of other crops, such as oats, growing among the lupin roots, can also take up some of this dissolved phosphate;[2] hence, such crops can make more growth, and suffer less from phosphate starvation, when growing with lupins than when growing alone.

E. E. De Turk[3] states that in Illinois sweet clover plays the same role as lupins. On the poor acid soils, regular additions of limestone and the regular use of sweet clover as a green manure catch crop increase very considerably the phosphate status of the surface soil, and this can be still further increased if the sweet clover is manured with rock phosphate, for it converts some of this relatively unavailable fertiliser into a more readily available form.

The Potassium Compounds

The primary sources of potassium in the soil are the potassium-bearing minerals. The potash micas, biotite and muscovite, yield up

[1] H. Schander, *Bodenk. PflErnähr.*, 1941, **20**, 129.
[2] Domontovitch *et al.*, *Trans. Sov. Sect. Int. Soc. Soil Sci.*, Comm., IV, 1933, **2**, 214.
[3] *Illinois Agric. Exp. Sta., Bull.* 484, 1942.

their potassium fairly readily,[1] particularly if finely ground; and some biotites can do this so easily that they have been used as potassic fertilisers in Norway.[2] The potash felspar orthoclase does not weather so easily as the two micas, whilst microcline is very resistant to weathering and releases its potassium very slowly. Clay minerals, particularly those derived from micas, also contain some potassium, which may be released slowly by weathering. A second source of potassium is the exchangeable potassium, and a third source is the exchangeable potassium that has been converted into a non-exchangeable form, as described on p. 110. This is converted back slowly into the exchangeable form when the level of exchangeable potassium in the soil becomes very low.

TABLE 107

Mean Response of Sugar-beet to Potassic Fertiliser on Soils with different Contents of Exchangeable Potassium

English sugar-beet experiments made during 1936–46

Potassic fertiliser—1 cwt. K per acre (as 2 cwt. potassium chloride)

Exchangeable potassium determined by 0·5 N acetic acid

Response to potassic fertiliser measured in presence of 4 cwt. per acre ammonium sulphate

Acetic acid soluble potassium in mgm. per 100 gm. soil	Number of fields	Response of sugar-beet to potassic fertiliser. Extra sugar in cwt. per acre
Below 5 . .	63	4·7
5–6·5 .	61	4·4
6·5–9 .	62	2·0
Over 10 . .	62	0·8

The primary source of potassium for plants is the exchangeable potassium,[3] and its level in the soil is an important factor in determining the responsiveness of a crop to a potassic fertiliser. This is illustrated in Table 107,[4] which shows the response of sugar-beet to potassic fertilisers in a large number of English experiments. Exchangeable potassium is quite obviously an important, though not the only, factor affecting the responsiveness of the crop to the potassic fertiliser.

Plants remove more potassium from the soil during the growing season than corresponds to the reduction in the exchangeable potassium

[1] I. A. Dennison, W. H. Fry and P. L. Gile, *U.S. Dept. Agric., Tech. Bull.* 128, 1929.
[2] P. Solberg, *Meld. Norg. LandbrHögsk.*, 1928, **8**.
[3] R. Stewart, *J. Agric. Sci.*, 1929, **19**, 524 (for some Scottish soils); R. H. Bray, *Soil Sci.*, 1944, **58**, 305 (for some Illinois soils).
[4] E. M. Crowther, *Bath and West Agric. Soc., Pamph.* 13, 1948.

content, but the amount of non-exchangeable potassium they use from a given soil depends to some extent on the crop. These non-exchangeable sources may be as important when the exchangeable potassium is high as when it is low, as is shown in Table 108.[1] Soils differ, however, very considerably in the rate at which they release their non-exchangeable potassium. The rate of release is naturally more important in soils with small amounts of exchangeable potassium.[2] Soils undergoing rapid weathering, as, for example, young soils being derived from basic igneous rocks in humid tropical climates,

TABLE 108

Uptake of Exchangeable and Non-exchangeable Potassium from some Texas Soils

5 kg. soil in large container, crop of maize and of kafir or sorghum taken

Quantities of K in parts per million of soil

Number of soils tested	Amount of K removed by crop		Loss of exchangeable K from soil	Exchangeable K in soil before cropping	Non-exchangeable K released by soils
	between	mean	mean	mean	mean
11	0 and 41	35	17	100	18
20	42 and 83	66	25	110	41
31	81 and 165	120	50	167	70
7	415 and 580	490	216	504	274

release very large amounts of potassium in an available form annually. Thus, H. W. van der Marel[3] finds that soils rich in biotite and andesine in Sumatra can yield up 200 to 250 kg. per hectare of potassium to crops such as sisal and sugar-cane indefinitely without becoming impoverished in potassium, and as an extreme example, A. S. Ayres and his co-workers[4] in Hawaii grew sixteen crops of elephant grass (*Pennisetum purpureum*) in four and a half years, and found each removed about 250 lb. of potassium per acre without appreciably affecting the content of exchangeable potassium in the top 3 feet of soil.

The discussion so far has assumed that soil minerals release potassium into the soil and the plant roots then take it up. But this over-simplifies the problem: plant roots can take an active part in helping minerals to

[1] G. S. Fraps, *Texas Agric. Expt. Sta., Bull.* 391, 1929. See also for similar results R. F. Chandler *et al.*, *J. Amer. Soc. Agron.*, 1945, **37**, 709, using Ladino white clover.

[2] D. R. Hoagland and J. C. Martin, *Soil Sci.*, 1933, **36**, 1; F. E. Bear *et al.*, ibid., 1944, **58**, 139; E. H. Stewart and N. J. Volk, *Soil Sci.*, 1946, **61**, 125.

[3] *Soil Sci.*, 1947, **64**, 445.

[4] *Proc. Soil Sci. Soc. Amer.*, 1947, **11**, 175.

release potassium. Very little work has been done on this aspect of the problem, though C. C. Lewis and W. C. Eisenmenger[1] have recently shown that different families of plants have very different abilities to extract potassium from an orthoclase felspar.

Some soils possess considerable power of converting added potassium into forms unavailable to the plant, as is shown in Fig. 45, for some Californian soils.[2] The reason why soils 29 and 80 in this figure fixed so much more potassium than the other soils was not investigated and is not known.

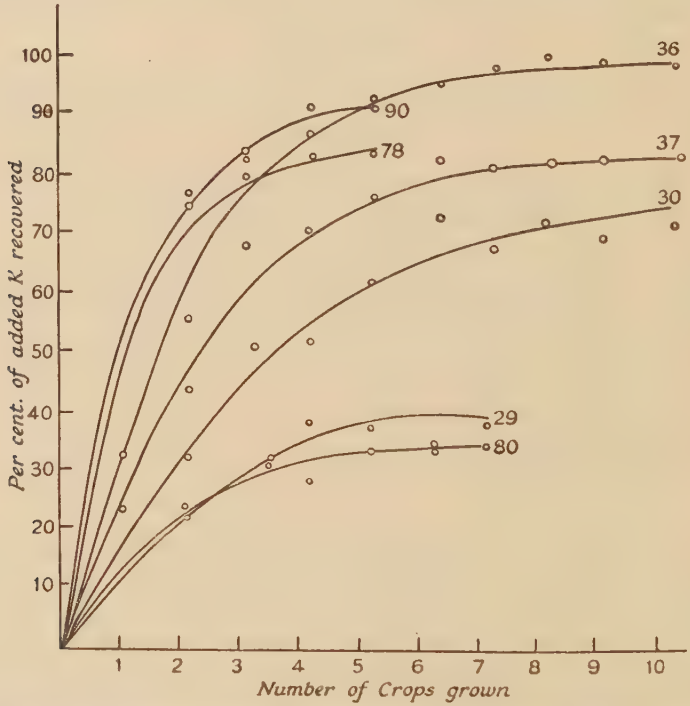


Fig. 45. Recovery of added potassium by a succession of barley and tomato crops grown in different soils.

For soils 30, 36 and 37, crops 1, 2, 4, 7 and 9 were barley, while crops 3, 5, 6, 8 and 10 were tomato; for soils 29, 78, 80 and 90, crops 1, 3, 5 and 7 were barley, while crops 2, 4 and 6 were tomato. (Recovery calculated on basis of comparison between NP and NPK fertilised soils.)

The Calcium Compounds

These fall into four groups:

1. Calcium present in the mineral particles. These calcium-containing minerals are nearly all primary, such as basic plagioclases rich in anorthite, epidote, and some constituents of basic rocks such as

[1] *Soil Sci.*, 1948, **65**, 495.

[2] D. R. Hoagland and J. C. Martin, *Trans. 3rd Int. Congr. Soil Sci.*, Oxford, 1935, **1**, 99.

gabbros, basalts and diabases. They all weather fairly readily, particularly if finely ground, yielding up their calcium.

2. Calcium carbonate, normally the most important source of calcium in soils.

3. Simple salts. (*a*) Calcium ions are usually the dominant cation in the soil solution: they cannot be considered as attached to any particular anion, though the two main anions they balance are nitrate and bicarbonate. (*b*) Calcium phosphate, mainly in the form of apatites, but this is usually only present in small quantities. (*c*) Calcium sulphate as gypsum, usually only important in arid soils though it occurs in considerable quantities in the lower layers of some English clays, such as the Kimmeridge.

4. Exchangeable calcium.

Calcium differs from phosphorus and potassium in that the calcium of simple compounds added to a soil remains available to plants until it is removed from the soil either by leaching or by being taken up by the plant. Perhaps the only mechanism whereby calcium can become fixed in the soil is in combination with phosphate in mildly acid to alkaline soils.

The exchangeable calcium in a soil is not all equally easily available to the plant. Calcium saturated montmorillonitic clays yield up their calcium with increasing difficulty as they become progressively unsaturated, but this property is displayed less strongly in clays of the illite type and still less by the kaolinitic clays or soil organic matter.[1]

The Manganese Compounds

Manganese occurs in many primary rocks, particularly in ferromagnesian rocks rich in iron. It also occurs in many soils as MnO_2, often in a hydrated form, and possibly also as trivalent manganese, though where this is held is not known. Soils also contain divalent manganese, present as an exchangeable cation.

The mechanisms by which soils supply an adequate quantity of manganese to plants are still far from elucidated. Plants can certainly use divalent and almost certainly cannot use tetravalent manganese, though whether they can use trivalent manganese, and if so, whether they take up any appreciable proportion of their manganese in this form is quite unknown. In practice, the problem is to maintain a reasonable, but not excessive, concentration of divalent manganese in the soil.

The factors controlling the proportion of soil manganese in the divalent form appear to be bound up with the form of the organic

[1] W. H. Allaway, *Soil Sci.*, 1945, **59**, 207; A. Mehlich and W. E. Colwell, ibid., 1946, **61**, 369.

matter present and the microbiological conditions prevailing. Three processes seem to be important in this connection:

1. Hydrated manganese dioxide is reduced to divalent manganese by bacteria in the presence of a suitable hydrogen donator and carrier, as, for example, sugars and acetates with pyocyanine as carrier.[1] Thus, water-logging a soil and then draining it, a condition that often arises in countries with cool, moist winters, increases the amount of divalent manganese in the soil.[2] It can be reduced in the field by adding hydroquinone or creatinine,[3] and this reduction can take place without the aid of micro-organisms.[4] In fact, phenol in acid soils, polyhydric phenols and sulphydryl compounds, such as cysteine in acid or alkaline soils, and hydroxy-acids, such as citric,[5] can all bring about reduction of the hydrated dioxide to manganous ions.

2. Divalent manganese is oxidised by certain soil bacteria to hydrated manganese dioxide,[6] and this oxidation can be much reduced by certain inhibitors, such as sodium azide or chloretone.[4] V. B. D. Skerman and S. M. Bromfield[7] have made the interesting observation that single species of bacteria, in pure culture, cannot bring about this oxidation: it was necessary to use pairs of suitable species. These bacteria congregate round the roots of some plants, and thus prevent them taking up manganese. This trouble can often be cured by partial sterilisation, which seems to reduce the activity of these bacteria markedly.[8]

3. Certain types of readily soluble soil organic matter can absorb divalent manganese and other metallic ions such as iron and copper, forming insoluble co-ordination compounds. This manganese is not exchangeable nor available to the plant, though it can be extracted both by neutral pyrophosphate and by some hydroxy-acids capable of forming co-ordination compounds with these metals.[9]

C. K. Fujimoto and G. D. Sherman have found that two other factors influence the level of exchangeable divalent manganese in the soil. Steam sterilisation can sometimes increase its level considerably, enough in fact for crop growth to be limited by manganese toxicity,[10] and a surface mulch can reduce it;[11] but the reason for neither of these is known.

[1] G. D. Sherman and P. M. Harmer, *Proc. Soil Sci. Soc. Amer.*, 1943, **7**, 398.
[2] G. W. Leeper, *Soil Sci.*, 1947, **63**, 79.
[3] F. Steenbjerg, *Tidskr. Planteavl*, 1934, **40**, 337; G. D. Sherman and P. M. Harmer, *J. Amer. Soc. Agron.*, 1941, **33**, 1080.
[4] P. J. G. Mann and J. H. Quastel, *Nature*, 1946, **158**, 154.
[5] P. J. G. Mann and S. G. Heintze, *J. Agric. Sci.*, 1947, **37**, 23.
[6] F. C. Gerretsen, *Verslag. Landbouwk. Onderzoek.*, 1936, **42** A, 57; G. W. Leeper and R. J. Swaby, *Soil Sci.*, 1940, **49**, 163; J. D. MacLachlan, *Sci. Agric.*, 1941, **22**, 201.
[7] *Nature*, 1949, **163**, 575. [8] M. I. Timonin, *Proc. Soil Sci. Soc. Amer.*, 1947, **11**, 284.
[9] J. M. Bremner *et al.*, *Nature*, 1946, **158**, 790; S. Mattson, *LantbrHögsk. Ann.*, 1948, **15**, 291.
[10] *J. Amer. Soc. Agron.*, 1948, **40**, 527.
[11] *Proc. Soil Sci. Soc. Amer.*, 1947, **11**, 206.

The net effect of these processes is that acid mineral soils are usually well supplied, and sometimes over supplied with divalent manganese; that calcareous soils are usually very low in divalent manganese; that many organic soils, in spite of containing considerable quantities of total manganese, are very poor suppliers of manganese to the crop; and that crops suffering from manganese deficiency diseases on either of these types of soil need far less manganese to be given them if it is sprayed on their foliage than if it is applied to the soil. It is possible, however, that adding sufficient sulphur to an organic soil to bring its *p*H below 7 may be as effective as adding manganese.[1]

The Sulphur Compounds

Sulphur normally occurs in primary rocks as sulphides, and tends to be higher in basic than in acid igneous rocks. These sulphides oxidise fairly readily in well-aerated soils, so that sulphate is the normal form of the inorganic sulphur in well-drained soils. Rain also brings down small amounts of sulphur as sulphur dioxide, but this is only appreciable in the neighbourhood of industrial towns. The main source of new sulphates in most soils is in the superphosphate added, for ordinary 16 to 20 per cent superphosphate contains about 60 per cent of calcium sulphate.

The main reservoir of available sulphur in most agricultural soils is, however, in the organic matter, for plants take up sulphates from the soil and use them in the synthesis of the amino acids cystine and cysteine, which form a part of many plant proteins. When the plant residues are returned to the soil and attacked by the soil fauna and micro-organisms, some of the sulphur reappears as sulphate, though much remains as part of the soil humus. The sulphur chemistry during humus formation is quite unknown; but, as was discusssed on p. 274, the sulphur contents of some Minnesota soils range from about one-hundredth of the carbon content in the prairie soils to between a half and a quarter of this proportion in the podzolic soils.[2]

Little is known about the processes by which organic sulphur is converted into sulphates in well-drained soils and into sulphides if anaerobic conditions set in, for these are the only two simple sulphur compounds present. The first product is probably hydrogen sulphide, or possibly a mercaptan,[3] which can be produced by many micro-organisms from sulphur-containing proteins, and this is then oxidised to sulphates if the oxygen supply is adequate. Probably also many

[1] G. D. Sherman and P. M. Harmer, *J. Amer. Soc. Agron.*, 1941, **33**, 1080; J. H. Quastel *et al.*, *J. Agric. Sci.*, 1948, **38**, 315.
[2] C. A. Evans and C. O. Rost, *Soil Sci.*, 1945, **59**, 125.
[3] H. L. A. Tarr, *Biochem. J.*, 1933, **27**, 1869.

organisms can reduce sulphates to sulphides whenever the oxygen supply in the soil becomes too restricted.

There is another reaction of great importance in some arid soils, namely, the oxidation of elementary sulphur to sulphates, for adding sulphur to an alkaline soil is one of the standard ways of lowering its *p*H (see p. 561). The only organisms that have definitely been proved to carry out this oxidation are some autotrophic species of the *Thiobacillus* group of bacteria,[1] which appear to be naturally widespread in alkaline soils.

The Nitrogen Compounds

The nitrogen compounds in the soil are derived mainly from proteins synthesised by the plants growing on the soil or by the soil organisms living in the soil, though very little is known about the actual chemical combinations in which they occur. They can, however, be divided into three groups:

1. Nitrogen present as nitrate or ammonium ions, which rarely account for more than 1 to 2 per cent of the total nitrogen present, but which forms the primary source of nitrogen for the crop.
2. Nitrogen present in compounds that decompose fairly readily to give ammonium or nitrate ions, often known as the nitrifiable nitrogen compounds.
3. Nitrogen present in compounds that are only slowly decomposed by the soil population.

There is naturally no sharp division between the second and third groups, but the division has been found useful, particularly under some conditions.

The amount of nitrogen in the soil that is available to the crop during the growing season depends on the rate of nitrate production in the surface soil during the season, and also on the amount of nitrates produced in the previous season that are stored in the subsoil within the range of the crop roots. The rate of nitrate production in the surface soil depends both on the amount and nitrogen content of the readily oxidisable organic matter present, and on the actual rate of oxidation, and this latter is only rapid in moist, well aerated soils.

The quantity of nitrates that can be stored in the subsoil, and the depth from which plant roots can extract this nitrate, depends very largely on the climate. F. J. Sievers and H. F. Holtz[2] showed that on the heavyish soils in the Palouse area much of the nitrates produced during a summer fallow were washed down by the winter rains to a depth

[1] For an account of the chemistry of this oxidation, see K. G. Voglu *et al.*, *J. Gen. Physiol.*, 1942, **26**, 89, 103, 157.

[2] *Washington Agric. Expt. Sta., Bull.* 166, 1922.

between 2 and 5 feet, though some was held in the sixth foot and doubtless some was washed out by the rains; and they showed that the subsequent wheat crop could use much of these nitrates held in the subsoil.

The reason that heavy soils can hold nitrates in their subsoil against drainage during winter is presumably because the drainage water can only move down through cracks and channels in the soil whilst the nitrates can be held inside the principal structural units in the subsoil, through which the drainage water cannot move. Thus, R. Warington[1] long ago showed that the composition of the water first draining out of Broadbalk field at Rothamsted after a heavy rain had almost the same composition as the rain-water itself: it was only in the last runnings that its composition approached that of the soil solution.

This concept of subsoil storage of nitrates over winter on heavy soils explains a number of observations that are otherwise difficult to understand.[2] In the first place, it is only possible on the heavier soils, for in the lighter the main drainage channels are closer together and more evenly distributed throughout the soil, hence there is a much smaller volume of soil available for holding nitrates against drainage. In consequence, it is only on the heavier lands that rotational fallowing is practised, for it is only these that can hold the nitrates produced in the surface soil by the summer cultivations for the use of a crop in the following year.

TABLE 109

Response of Wheat to a One-year Fallow: Broadbalk, 1935–45

Yield in dressed grain in bushels per acre

Nitrogen manuring in lb. per acre of nitrogen as sulphate of ammonia per year	Years after fallow			Increase in yield over the third and fourth year	
	First	Second	Third and fourth	In first year	In second year
0	30·8	15·1	14·0	15·8	1·1
43	36·2	24·0	22·7	13·5	1·3
86	38·7	30·1	29·3	9·4	0·8
129	39·5	35·2	32·7	6·8	2·5

The effects of rotational fallowing on the wheat yield on Broadbalk furnishes an excellent example of this effect. Table 109 shows that one year's fallow adds the equivalent of about 90 lb. per acre of nitrate nitrogen, which, as Fig. 22 on p. 293 shows, is considerably less than the extra nitrate nitrogen found in the top 18 inches of soil during the fallowing, for it corresponds to between 15 and 20 p.p.m. of nitrate

[1] *J. Roy. Agric. Soc. England*, 1882, **18**, 1.
[2] E. M. Crowther, *Trans. 3rd Int. Congr. Soil Sci.*, Oxford, 1935, **3**, 126.

nitrogen throughout this depth of soil. Yet, as both this figure shows, and as has been subsequently confirmed by J. B. Marshall in 1935,[1] the nitrate nitrogen content in the top 18 inches of fallow soil during the winter is almost the same as in the cropped soil. Hence, this nitrate is presumably held in the subsoil.

This has not been directly proved at Rothamsted because the soil is a gravelly clay, and hence deep subsoil sampling is difficult, but it can be deduced from the response of the following wheat crop to rainfall. The response of wheat to fallow is independent of the winter rainfall, but it is much reduced if the late spring and early summer are wet, presumably because under these moist conditions the wheat remains shallow rooted, and hence its roots do not reach the nitrates stored in the subsoil. This result can be tested in another way on Broadbalk, for on one plot all the sulphate of ammonia given to the wheat is applied in the autumn whilst on the others one quarter is applied in the autumn and three quarters in the spring. The difference between the responses of the wheat to these two treatments does not depend on the winter rainfall, but the autumn nitrogen becomes increasingly ineffective as the late spring and early summer rainfall increases.[2]

On light sandy soils this subsoil storage of nitrates is not possible during moist winters, such as usually occur in the British Isles. Hence, the ideal way for such a soil to carry a store of available nitrogen over the winter is in a succulent green crop which is ploughed in in the spring just before the main crop is to be sown. This is particularly effective if the crop is well established before the winter rains begin and the climate is sufficiently mild for the crop to grow continuously and hence to take nitrates from the soil, during this season. However, over much of this country catch crops have not made much growth before winter begins and make very little during the winter, and this limits the use of green manuring to a few favoured districts only.

The Organic Matter

It has already been stated (see p. 25) that there is no evidence that any of the organic compounds in the soil organic matter are direct nutrients for the plant, yet in many natural soils high crop yields can only be secured if there is an adequate supply of suitable organic matter.

Experimental evidence for the first part of this statement can be found in the Rothamsted field experiments with cereals. Average yields of wheat, barley and mangolds on land that has received adequate

[1] Unpublished Ph.D. Thesis, London. [2] "*Alumnus*", *J. Agric. Sci.*, 1932, **22**, 101.

fertiliser dressings but no farmyard manure for eighty to a hundred years are as good as on land that has received generous dressings of farmyard manure every year, although the yields on the fertiliser plots are rather more variable. But this could be due to the better physical condition of the manured plots.

A more detailed comparison of fertilisers with farmyard manure was made over a twenty-year period at Askov, in which amounts of fertiliser strictly comparable to that in the farmyard manure were used. Here the fertilisers proved distinctly superior to the manure: indeed, it took twice as much nutrient in the form of farmyard manure to give the same effect as a given dressing of fertiliser.[1]

There are, however, crops that seem to respond especially well to manure in a way that they do not to fertilisers. An example of this has already been given for potatoes on p. 63, and certain fruit bushes may also show this behaviour. But in these examples the improvement in soil condition brought about by the manure is probably a sufficient explanation of its additional beneficial effect. Beans also have been suspected of responding to farmyard manure over and above that due to the nutrients it contains, but there are not sufficient experiments to decide yet if this is a fact, because in much of the earlier work the need for potassium, which is present in considerable quantities in good farmyard manure, was not realised.

Farmyard manure, and other organic manures, can, however, have another very important function in the soil, for they maintain in it an adequate supply of iron[2] and other trace elements needed by the crop in a form available to the crop. This function is particularly important in soils where these elements are rapidly converted into an unavailable form. The mechanism of this process is probably the slow release of these elements during the decomposition of the organic matter, though the possibility of other mechanisms for preventing these elements from being converted into unavailable forms cannot be ruled out. Farmyard manure can even be a valuable carrier of phosphate, and K. T. Hartley[3] has given an example from Nigeria of the great benefit crops receive from dressings as low as 1 to 2 tons per acre of farmyard manure. Here the manure decomposes and releases its phosphate so rapidly that the crop can take up the bulk of it, for 1 ton of manure only contains the same total amount of phosphate as 64 lb. of superphosphate.

Humic colloids, as distinct from decomposing organic matter, may

[1] K. Iversen, *Ztschr. Pflanz. Düng.*, 1928, B **7**, 457. Reviews of the older work by O. Lemmermann, ibid., 1932, B **11**, 1; M. Gerlach, ibid., p. 385; A. W. Blair, *J. Amer. Soc. Agron.*, 1933, 25, 540, lead to the general conclusion that after allowing for ordinary nutritive and physical effects there is little left to account for.

[2] J. Bonner, *Bot. Gaz.*, 1946, **108**, 267.

[3] *Emp. J. Expt. Agric.*, 1933, **1**, 113 (with M. Greenwood); 1937, **5**, 254.

also maintain some inorganic ions in a form available to plant roots under conditions when they would otherwise be converted into unavailable forms if the organic colloids were not present. Thus, humic colloids will help maintain iron and other trace elements in an available form in alkaline soils, and phosphates in an available form in acid soils containing active aluminium, as, for example, in many tropical soils.[1] Though humic colloids are probably the most important agency in the soil having this power, colloidal silicates can also fulfil the same function. Thus, A. Demolon and E. Bastisse[2] showed that the chlorosis of vines and fruit trees that may develop on calcareous soils can sometimes be cured by adding a silicate solution containing iron protected by colloidal silicates.

[1] R. Chaminade, *Ann. Agron.*, 1944, **14**, 1; 1946, **16**, 229; *C.R. Conf. Pédol. Méditerr.*, 1948, 222.

[2] *C.R. Acad. Agric.*, 1944, **30**, 501; *Ann. Agron.*, 1946, **16**, 434.

CHAPTER XXVII

THE EFFECT OF SOIL ACIDITY AND ALKALINITY ON PLANT GROWTH

The Effect of Soil Acidity

NATURAL SOILS DIFFER considerably in their reaction, or *p*H, and these differences are reflected in the vegetation or crops they carry. For a long time it was not clear how far these differences were due to the sensitivity of the plant roots to the hydrogen-ion concentration of the soil or soil solution in which they were growing, and how far to secondary effects brought about by the reaction. Water-culture experiments have now proved conclusively that the harmful effects of acidity are due to secondary causes, except in extreme cases. Thus, D. I. Arnon and his co-workers[1] showed that many crops would grow satisfactorily in solution whose *p*H ranged from *p*H 4 to 8, provided precautions are taken to eliminate harmful secondary effects, but that plant roots are definitely injured in solutions as acid as *p*H 3, and are unable to absorb phosphates at *p*H 9.

The secondary effects of high acidity, or low *p*H, in a soil are shortage of available calcium and sometimes phosphate on the one hand, and excess of soluble aluminium, manganese,[2] and perhaps other metallic ions on the other. The relative importance of these factors depends on the composition of the soil, in so far as it affects the level of available calcium, phosphate, aluminium and manganese, and on the susceptibility of the crop to a deficiency of calcium or an excess of aluminium or manganese. Excess manganese accumulates in all tissues and interferes with their proper metabolism. Excess aluminium accumulates in the roots[3] and may reduce very considerably their power of translocating phosphates from the soil to the vascular system.[4] Excess aluminium may therefore cause the plant to suffer from a phosphate starvation which cannot be corrected by adding phosphate to the soil.[5]

Crops differ in their susceptibilities to these consequences of acidity, hence it is impossible to draw up any table showing the critical *p*H at

[1] *Plant Physiol.*, 1942, **17**, 515, 525.

[2] For English figures, see T. Wallace *et al.*, *Nature*, 1945, **156**, 778; J. B. Hale and S. G. Heintze, ibid., 1946, **157**, 554. For American figures, see M. J. Funchess, *Alabama Agric. Exp. Sta., Bull.* 201, 1918; H. G. M. Jacobson and T. R. Swanbank, *J. Amer. Soc. Agron.*, 1932, **24**, 237.

[3] For a summary of the literature, see G. E. Hutchinson, *Quart. Rev. Biol.*, 1943, **18**, 128.

[4] K. E. Wright, *Plant Physiol.*, 1943, **18**, 708; E. J. Hewitt, *Long Ashton Ann. Rep.*, 1948, 58.

[5] I am indebted to Professor T. Wallace for this observation.

which a given crop begins to suffer severely from acidity, even if any definite meaning could be given to the *p*H figure. There is no necessary close connection between the *p*H of a soil and its suitability for a given crop in the moderately acid range.

The relative importance of the three major consequences of soil acidity—low calcium and high aluminium and manganese—affect different crops differently, and only recently has critical work been started to assess their relative importance. E. J. Hewitt,[1] of Long Ashton, has published some preliminary observations. He finds that sugar-beet and potatoes have a high calcium requirement, but whereas sugar-beet is relatively tolerant to high manganese and susceptible to high aluminium, potatoes tend to be relatively susceptible to manganese but tolerant to aluminium. The brassica crops are like potatoes and barley is like sugar-beet except they have lower calcium requirements, whilst oats is a reliable crop on all acid land as it has a low calcium requirement and is tolerant of high aluminium and high manganese. The legumes also differ among themselves in their tolerance to manganese. Thus, lespedeza and sweet clover are sensitive to a high level of manganese, groundnuts are tolerant and cow-peas and soybeans come intermediate;[2] yet lespedeza, for example, commonly grows well on very acid soils, which must, therefore, presumably be low in manganese.

The harmful effects of acidity can always be corrected by the judicious use of calcium carbonate, which raises the *p*H and the level of available calcium and lowers that of manganese and aluminium. But two of the harmful effects of acidity—low available calcium and sometimes high available manganese[3] can be mitigated by adding a soluble calcium salt, such as calcium sulphate, which has no effect on the *p*H of the soil. It increases the available calcium, and as a consequence decreases the relative ease of uptake of manganese by the plant roots, though the effect on the total manganese uptake by the plant is partially neutralised, or even reversed, by the increased manganese ion concentration in the soil solution due to base exchange. Potatoes, the brassica crops and legumes such as lespedeza and soybeans would be expected to respond to calcium sulphate for this reason. There is also the possibility that these crops will respond to dressings of calcium carbonate which are inadequate to affect the *p*H of the soil appreciably if it is added as a limestone ground fine enough for there to be a sufficient number of lumps close to all the principal roots of the crop, thus allowing each access to a calcium supply, but yet coarsely enough to dissolve so slowly in the soil that little is used for neutralising its

[1] *Long Ashton Ann. Rep.*, 1947, 82. [2] H. D. Morris and W. H. Pierre, *Agron. J.*, 1949, **41**, 107.
[3] For a successful example with lucerne, see E. H. Kipps, *J. Counc. Sci. Indust. Res.*, 1947, **20**, 176; for an unsuccessful one with lespedeza, see H. D. Morris, *Proc. Soil Sci. Soc. Amer.*, 1949, **13**, 362.

acidity. This may be the reason for the contradictory results that have been obtained on the effectiveness of limestones of different grades of coarseness, for whilst the general experience has been that finely ground limestone is at least as effective, and often more effective than coarsely ground in increasing crop yields on acid soils, yet there are observations[1] in which light dressings of coarse ground limestone have been more effective than equal dressings of fine ground.

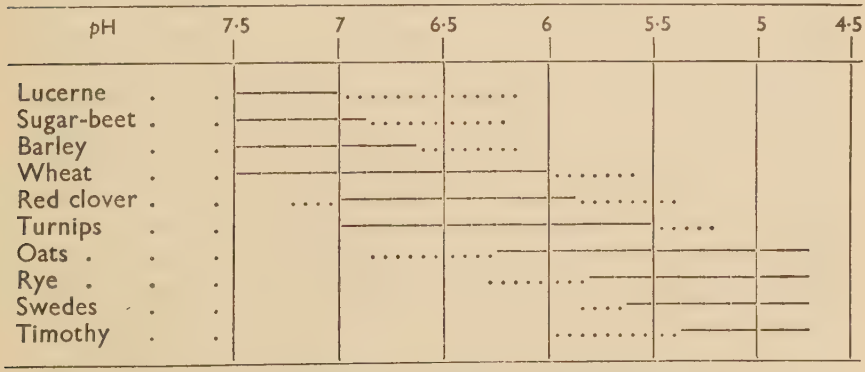
Some work of P. Tuorila[2] in Finland furnishes another interesting example of the complexity of the troubles due to soil acidity. He analysed the results of nearly a thousand field liming experiments and showed that the response of clay soils to calcium carbonate could be roughly predicted from their *p*H, but this was not possible for the sands: these appeared to need an adequate calcium supply, equal to nearly 5 tons per acre of calcium carbonate in the 8 inches of soil or to about 10 milli-equivalents of calcium per 100 grams of soil.

Lists can, however, be drawn up showing the crops that generally only do well on slightly acid to neutral soils, and those that will tolerate more acid conditions. Thus, in England, lucerne, barley, sugar-beet and mangolds are only considered suitable for neutral to mildly acid soils; wheat, red clover, peas, beans and vetches will often succeed in

TABLE 110

Soil Reaction and Plant Growth: Survey of about 200 Swedish Farms

The unbroken lines indicate frequent occurrence and good yields, the dotted lines poor yields and less common occurrence



[1] See, for example, W. A. Albrecht, *Soil Sci.*, 1946, **61**, 265.
[2] *Svenska Vall-o MosskFören. Tidskr.*, 1945, **7**, 83.

rather more acid soils; and white clover, many grasses, oats, rye, lupins and potatoes will grow on soils too acid for the others. Among sub-tropical crops tolerant of acid conditions are lespedeza, soybeans and some varieties of beans, millets, sorghums, including sudan grass, and sweet potatoes.

Table 110, which gives a summary of a cropping survey on 200 Swedish farms made by O. Arrhenius,[1] illustrates this by showing the actual cropping practised by farmers on soils of different *p*H. But this table must be correctly interpreted: it does not show the optimum value of the *p*H for any crop, but only the tolerance of the crop to acidity. Thus oats, rye, swedes and potatoes[2] can all be grown as successfully in neutral as in acid soils, though true calcifuge plants, such as lupins among agricultural crops, and heaths and rhododendrons among shrubs, will only thrive on acid land, probably because of their intolerance of a high level of calcium, though perhaps in part because they cannot obtain iron from nearly neutral soils.

A point of some importance arises here. If one has an acid soil, should one regard the acidity as inherent, and crop the soil accordingly with acid-tolerant crops, or should one neutralise the acidity and have greater freedom of cropping? The same point arises on low phosphate soils: should one choose crops that can stand low phosphate status, or should one raise the soil's phosphate status? In either case the undesirable condition may be aggravated by continuous cropping with tolerant crops.

Two other points on the effect of soil acidity on the distribution of crops can be made. Liberal dressings of farmyard manure ameliorate the effects of acidity, and for reasons not fully explained, crops are more tolerant of acidity in cool, moist climates than in warm, dry ones. Thus, crops can be successfully grown on more acid soils in parts of Wales, Scotland and Scandinavia than in the southern and eastern parts of England.

The second point is that variations in soil reactions may affect the susceptibility or resistance of the crop to a particular fungus disease. Thus, *Plasmodiophora brassicae*, the fungus that causes finger-and-toe, or club-root in the cultivated brassica crops (swedes, turnips, cabbage, etc.) tolerates soil acidity better than its host crop, and is therefore most likely to be injurious on acid soils. Addition of lime reduces the acidity and either makes the soil less suited to the pathogen or increases the resistance of crop to the fungus. Table 111 gives some examples of this correlation between the *p*H of the soil and the incidence of

[1] *Kalkfrage, Bodenreaktion und Pflanzenwachstum.*, Leipzig, 1926.

[2] For example, O. Smith (*Cornell Agric. Expt. Sta., Bull.* 664, 1937) found potatoes grew equally well in soil between *p*H 4·8 and 7·1.

TABLE III

pH Values for Pairs of Comparable Soils Differing as Habitats for Plants or Micro-organisms[1]

Centre	Crop	Condition	pH	Condition	pH
(1) Rothamsted	Swedes	Finger-and-toe	5·85	No finger-and-toe	7·90
,,	,,	,, ,,	6·05	,, ,,	7·87
(2) Garforth .	,,	,, ,,	5·66	,, ,,	6·13
(3) Aberdeen .	Turnips	Much finger-and-toe	6·21	Little finger-and-toe	7·13
(4) Somerset .	Barley	Failure	4·41	Good	5·77
(5) Ipswich .	Lucerne	,,	6·15	,,	7·86
(6) Carrington[2] Moss .	—	Uncultivated	3·01	Cultivated	5·52
	—	Bad field	4·88	Good field	5·14
(7) Pusey .	Potatoes	Much scab	7·40	Little Scab	6·13
	,,	,,	7·65	,,	6·75

the disease.[3] On the other hand, *Actinomycetes chromogenus* (*Oospora*), potato scab, is less tolerant of acidity than its host, and over a certain range potatoes can be grown well without fear of attack. Even though their soils need lime for other crops, Cheshire farmers do not add it until after the potatoes are lifted, otherwise "scab" may develop. Potatoes need calcium on more acid soils, but care must be exercised in applying lime or "scab" results. Thus, W. L. Nelson and N. C. Brady[4] found that potatoes growing on very acid soil (*p*H 4·2) could get all the calcium they needed if the lime was mixed with the subsoil only, so allowing the tubers themselves to grow in the surface soil that was too acid for the pathogen. The fungus causing "take-all" in wheat (*Ophiobolus graminis*) develops much more readily in slightly alkaline than in acid conditions: it is liable to do damage on calcareous soils, but not on slightly acid sands or heavy loams.

The effects of acidity are usually more marked in meadows and pastures than on arable land, for here very many species of plants are growing in competition with each other. Plants which tolerate acidity a little better than their neighbours will tend to spread at their expense, and come to dominate the flora of acid soils, though they do not necessarily thrive best in acid soils in the absence of competition. This effect of *p*H on the floristic composition of some Danish meadows is

[1] E. M. Crowther, *J. Agric. Sci.*, 1925, **15**, 201.
[2] These soils have been discussed by E. Price Evans, *J. Ecol.*, 1925, **11**, 64.
[3] For further field trials on the control of the disease by liming, see J. Hendrick, *Trans. Highl. Agric. Soc. Scotland*, 1918, **30**, 137.
[4] *Proc. Soil Sci. Soc. Amer.*, 1944, **8**, 313.

TABLE 112

Average Frequency[1] *of Meadow Species on Soils of Different pH Values*

pH range	3·5–3·9	4–4·4	4·5–4·9	5–5·4	5·5–5·9	6–6·4	6·5–6·9	7–7·4	7·5–7·9	No. of localities
Deschampsia flexuosa	86	68	40	—	—	—	—	—	—	13
Calluna vulgaris	20	47	10	20	—	—	—	—	—	13
Gallium hercynicum	94	77	40	20	15	—	—	—	—	18
Potentilla erectum	67	99	63	73	48	45	10	20	—	39
Agrostis canina	—	100	100	73	63	100	—	—	—	12
Festuca ovina	—	100	47	35	20	20	50	—	—	12
Anthoxanthum odoratum	33	47	79	80	83	76	27	30	30	46
Deschampsia caespitosa	—	—	—	40	67	62	33	52	23	33
Circium oleraceum	—	—	—	—	—	—	50	100	80	8
Angelica sylvestris	—	—	—	—	—	35	33	48	30	14
Tussilago farfara	—	—	—	—	—	10	10	55	80	9
Agrostis alba	—	—	—	—	—	—	30	65	60	7

illustrated in Table 112.[2] It is also well shown in the Rothamsted grass plots, in which the manuring has been unaltered for ninety years in some cases.[3] The effect of high acidity can be indirect, for when the soil becomes too acid, surface feeding species of earthworms and other insects die out, so there is no mechanism by which the dead herbage can be mixed with the soil. It forms a mat on the surface under which, and in which, the seedlings of most plants cannot germinate. Again, hill pastures in Great Britain can have the feeding value of their herbage greatly increased by liming and phosphating, for this causes the coarse *Nardus* and *Agrostis* grasses to be replaced by more nutritious species, such as rye-grass and rough- and smooth-stalked meadow grass.[4] Even on ordinary pastures the herbage depends on the acidity of the soil, and, as W. R. G. Atkins and E. W. Fenton[5] showed, cattle and sheep tend to graze the less acid areas more closely than the more acid ones. Thus they found the animals only reluctantly grazed the pasture where its *p*H was under 5, and preferred the areas where it was over 6·5.

[1] The frequency is determined on ten trial areas each of 0·1 sq. m. at each centre. If a plant is found on eight of these areas at one centre, the frequency is 80 per cent, The figures in the table are the average of the frequencies at all the centres.

[2] C. Olsen, *C.R. Lab. Carlsberg*, 1923, **15**, 1.

[3] For an account of the floristic composition of these plots, see W. E. Brenchley, *Manuring of Grassland for Hay*, London, 1924.

[4] See, for example, W. E. J. Milton, *J. Ecol.*, 1940, **28**, 326; 1947, **35**, 65.

[5] *Sci. Proc. Roy. Dublin Soc.*, 1930, **19**, 533.

The Effect of Soil Alkalinity

The harmful effects of high alkalinity are again usually due to consequences of the alkalinity rather than to the hydroxyl ions themselves. The great difficulties experienced by plants growing in alkaline soils are absorbing enough iron, manganese, boron and perhaps other trace elements on the one hand, and phosphates on the other, not because their roots are incapable of absorbing these nutrients from solutions at these *p*Hs, but because the nutrients are in so insoluble a form that the roots cannot bring enough of them into solution for their requirements. These harmful effects can often be seen when acid sandy soils, particularly when high in organic matter, are heavily limed.

Calcareous soils free from sodium salts cannot have a *p*H exceeding 8·2 to 8·4, for, as explained on p. 101, a moist calcareous soil would have a *p*H of 8·4 when in equilibrium with air having the same carbon dioxide content as in the atmosphere, and at this *p*H the concentration of these essential ions is too low for the plant to obtain an adequate supply.

The maximum *p*H which a soil can have for these ions to be present in an adequate concentration for the crop has not been worked out, and in fact this particular problem is probably not worth the tackling because of the inherent limitations in the meaning that can be given to the phrase "the *p*H of the soil". But the *p*H of the soil solution in a calcareous soil, which is an important factor controlling the availability of these nutrient ions, depends on its carbon dioxide content,[1] hence the problem that probably can be profitably investigated is to find the minimum carbon dioxide content of the soil air that allows the crop to take up enough of these nutrients.

The consequences of the variations of carbon dioxide content on the availability of these nutrients in different types of calcareous soils have not been worked out quantitatively.[2] But the general consequences are clear. Sandy soils are usually better aerated than loams and clays, and nutritional troubles due to over-liming are usually confined to such soils. The carbon dioxide concentration in a soil can be increased by rolling it, and heavy rolling is essential on many of the lighter calcareous soils for good germination and early growth. Pastures have a higher carbon dioxide content than arable, and grassing down miserable orchards on light or thin calcareous soils often increases their health and vigour markedly. This is not to imply that *p*H or carbon dioxide content of the

[1] For illustrations of the importance of this for phosphate uptake, see T. F. Buehrer, *Arizona Agric. Exp. Sta., Tech. Bull.*, 42, 1932; W. T. McGeorge *et al.*, *J. Amer. Soc. Agron.*, 1935, **27**, 330.

[2] For an example of the effect of the CO_2 content of soil water on the level of available manganese in a soil, see B.D. Bolas, *Nature*, 1948, **162**, 737.

soil air is the sole factor responsible for the nutrient deficiencies that occur on calcareous or over-limed soils, for some of the factors that increase the carbon dioxide concentration in the soil also increase the amount of potassium taken up by the crop, for some reason not yet explained (see p. 587). Further, as T. Wallace and E. J. Hewitt[1] have pointed out, anything that increases the potassium uptake in calcareous soils is particularly important because potassium deficiency sometimes induces iron deficiency or chlorosis—one of the characteristic troubles of calcareous soils.

A practical consequence of this danger of over-liming is that naturally well aerated soils, such as light sands and many peats, must never be given large dressings of calcium carbonate, for this either causes the whole soil, or very many pockets in the soil to have too high a *p*H. It is usually desirable to aim at maintaining the *p*H of such soils at under rather than over 6·5, and they should be given frequent light applications of lime. Very difficult problems may arise, however, when one sets out to reclaim a very acid heath: one must normally apply only sufficient lime to allow acid tolerant crops such as potatoes and rye to be grown and slowly increase the calcium status until the full range of farm crops can be taken.

Soils can only have *p*Hs exceeding 8·4 if they contain appreciable quantities of exchangeable sodium. The maximum recorded *p*H for a soil is probably 10·0 for an alkali soil at field capacity containing sodium carbonate in the State of Washington:[2] its *p*H in a 1 : 5 water suspension was 10·75. Soils containing exchangeable sodium but no calcium carbonate can, in fact, have their *p*Hs raised to high values by applying calcium carbonate, for this allows some sodium carbonate to be formed by exchange.

In humid soils the main change of reaction that one wants to bring about is raising the *p*H, but in arid regions it is often desirable to lower it. One way of doing this is to increase the CO_2 content in the soil air, by, for example, ploughing in manure or green manure. Another way is to apply sulphur to the soil, which is oxidised to sulphuric acid by certain soil bacteria that seem to be widely distributed in alkaline soils. Aluminium sulphate has also been used, for the aluminium is precipitated either as hydroxide or basic sulphate with the liberating of sulphuric acid, but it is not as efficient as sulphur on the basis of equal sulphur contents. These two methods can naturally be combined in the use of sulphur composts, made by adding sulphur to the plant residues when they are put into the compost heap, and this is probably the most satisfactory method for horticultural or

[1] *J. Pomol.*, 1946, **22**, 153.
[2] W. P. Kelley and S. M. Brown, *J. Amer. Soc. Agron.*, 1939, **31**, 41.

orchard crops. These methods are, however, discussed in more detail on p. 561.

W. T. McGeorge[1] has given examples of the value of adding sulphur or other acid materials to fertilisers to improve their effectiveness on alkaline soils. The sulphur, by increasing the soil acidity, helps the crop to take up more iron, manganese and often zinc, as well as phosphate, and, in fact, the use of acid phosphates, or sulphur-phosphate mixtures is strongly recommended for the Arizona conditions. In the same way ammonium fertilisers are usually more effective than nitrates,[2] presumably because they tend to leave the soil more acid.

[1] *Arizona Agric. Expt. Sta., Tech. Bull.* 101, 1943.
[2] K. Mehring, *Landw. Jahrb.*, 1935, **79**, 481.

CHAPTER XXVIII

THE EFFECT OF A GROWING PLANT ON THE SOIL

LIVING PLANT ROOTS can affect the biotic conditions in the soil by their differential absorption of nutrients from it and by their excretions into it.

Plant roots take up their anions and cations preferentially, so do not necessarily take equivalent quantities of each from the soil solution. Hence, the plant may cause a shift in the *p*H of the soil for this reason. This effect has been known for a long time. Thus, W. Knop[1] found that if plants grew in culture solution containing nitrates the solution became progressively more alkaline until the plants suffered from chlorosis and died. Shortly afterwards F. Rautenberg and G. Kühn[2] found that if the culture solution contained ammonium salts it became progressively more acid. In 1881 A. Mayer,[3] in discussing some of the erratic results obtained with potassic fertilisers, suggested that the preferential uptake of potassium by plants might produce acidity in the same way as with ammonium salts. He introduced a classification of fertilisers into—

(1) Physiologically acid, e.g. ammonium and potassium salts.
(2) Physiologically neutral, e.g. calcium and magnesium sulphates, superphosphates and calcium chloride.
(3) Physiologically alkaline, e.g. Chilean nitrate, calcium carbonate, lime.

These results, based on the results of pot experiments, cannot properly be used to estimate the corresponding effect of the fertiliser in the soil. Thus, in arable soils acidification by ammonium salts is primarily due to nitrification, but the term physiological acidity may be retained if it is extended to include the removal of ammonium by micro-organisms as well as by plants. Nitrates undoubtedly conserve soil bases and reduce soil acidity and may correctly be termed physiologically basic in Mayer's sense. Potassium salts have no appreciable effect on soil reaction and are not physiologically acid in this wider sense, although in culture solutions and in sand the acidity produced by growing plants may be measured and used to increase the availability of relatively insoluble phosphates.[4] Mayer correctly regarded superphosphate as physiologically neutral in spite of the acidity of its solutions, but many

[1] *Landw. Vers.-Stat.*, 1861, **3**, 295. [2] *Landw. Vers.-Stat.*, 1864, **6**, 358.
[3] *Landw. Vers.-Stat.*, 1881, **26**, 77; *J. f. Landw.*, 1864, **12**, 107.
[4] D. N. Prianischnikov, *Die Düngerlehre*, Berlin, 1923; *Ztschr. Pflanz. Düng.*, 1933, A **30**, 38.

later writers erroneously assumed that superphosphate increased soil acidity. Alkaline materials, such as lime or basic slag, should not be described as "physiologically" basic.

Plants take up different amounts and different proportions of nutrients from a soil according to their species. The exact amounts taken up depend on the soil conditions (see p. 435), but certain broad generalisations can be made. Table 113 shows typical quantities of

TABLE 113

Amounts of Various Substances Absorbed from an Acre of Soil by the Common Agricultural Crops of England

	At harvest lb.*	Dry lb.*	Total pure ash lb.	Nitrogen lb.	Sulphur lb.	Potassium lb.	Sodium lb.	Calcium lb.	Magnesium lb.	Phosphorus lb.	Chlorine lb.	Silicon lb.
Wheat, grain, 30 bush.	1800	1530	30	34	2·7	7·7	0·5	0·7	2·2	6·2	0·1	0·3
straw . .	3160	2650	142	16	5·1	16·2	1·5	5·9	2·1	3·0	2·4	45·0
Total crop . .	4960	4180	172	50	7·8	23·9	2·0	6·6	4·3	9·2	2·5	45·3
Oats, grain, 45 bush. .	1890	1630	51	34	3·2	7·5	0·6	1·3	2·2	5·7	0·5	9·3
straw . .	2830	2350	140	18	4·8	30·7	3·4	7·0	3·1	2·8	6·1	30·6
Total crop . .	4720	3980	191	52	8·0	38·2	4·0	8·3	5·3	8·5	6·6	39·9
Beans, grain, 30 bush. .	1920	1610	58	78	4·4	20·2	0·4	2·1	2·5	10·0	1·1	0·2
straw . .	2240	1850	99	29	4·9	35·5	1·3	18·8	3·4	2·7	4·3	3·2
Total crop . . .	4160	3460	157	107	9·3	55·7	1·7	20·9	5·9	12·7	5·4	3·4
Meadow hay, 1½ tons .	3360	2820	203	49	5·7	42·3	6·8	22·9	8·7	5·4	14·6	26·6
Red clover hay, 2 tons	4480	3760	258	98	9·4	69·1	3·8	64·4	17·0	10·9	9·8	3·3
Turnips, roots, 17 tons	38100	3130	218	61	15·2	90·1	12·6	18·2	3·4	9·8	10·9	1·2
leaf . .	11400	1530	146	49	5·7	33·4	5·6	34·6	2·3	4·7	11·2	2·4
Total crop . . .	49500	4660	364	110	20·9	123·5	18·2	52·8	5·7	14·5	22·1	3·6
Mangolds, roots, 22 tons	49300	5910	426	98	4·9	185·0	51·5	11·3	11·0	15·4	42·5	4·1
leaf . .	18200	1650	254	51	9·1	64·7	36·6	19·3	14·6	7·6	40·6	4·3
Total crop . . .	67500	7560	680	149	14·0	249·7	88·1	30·6	25·6	23·0	83·1	8·4
Potatoes, tubers, 6 tons	13400	3360	127	46	2·7	63·5	2·8	2·4	3·8	9·4	4·4	1·2

* Weight of crop. The yields quoted are not averages, though they are commonly obtained on farms.

various substances English crops remove from the soil,[1] and E. Wolff[2] and H. Wilfarth and his co-workers[3] have published other tables. They all show that cereals absorb less mineral nutrients per acre than any other crop studied, although they give a large amount of dry matter per acre. The animal fodder crops—grass and clover hay and the root crops—all take up large amounts of nutrients, and hence the need for good conservation of the nutrients in farmyard manure made from these crops, otherwise the soil will rapidly become impoverished. A consequence of this differential absorption of nutrients by crops is that if the nutrient status of the soil is low, crops taking large amounts of nutrients from a soil leave it poorer than crops only taking small

[1] R. Warington, *The Chemistry of the Farm*, 4th ed., London, 1886.
[2] *Aschen Analysen*, Berlin, 1871. [3] *Landw. Vers.-Stat.*, 1905, **63**, 1.

amounts of nutrients. Thus, on acid soils with low base reserves at the Rhode Island Station[1] crops sensitive to acidity do much worse after mangolds, which take up large amounts of base, than after the grass red top (*Agrostis alba*) which takes up much less.

Roots excrete carbon dioxide, or carbonic acid, into the soil solution, but this will only affect the acidity of the soil, or its base reserves, in so far as the carbonic acid is neutralised by calcium and washed out as calcium bicarbonate during periods of strong leaching. It will normally not affect the soil acidity in so far as the carbon dioxide excreted enters the soil air and is exchanged for atmospheric oxygen by diffusion.

Some plant roots excrete substances that are harmful to young roots of other plants (see p. 493); some varieties of flax excrete prussic acid, HCN, which protects their roots from attack by some pathogenic fungi (see p. 216); some species of lupins apparently excrete acids that can bring relatively insoluble phosphates into solution (see p. 461). Plant roots probably also excrete enzymes such as ureases and phosphatases into the soil, but these may be introduced through the sloughing-off and decomposition of dead tissue and not be an actual excretion, though the separation of these two processes may be very artificial. Plant roots also probably supply the soil micro-organisms with some nutrients and growth factors, for they often carry a large microbial population (see p. 214), but although part of these nutrients may be excreted by the roots,[2] the organisms may also take a proportion from the outer cells of the roots, possibly through the agency of fungi that have part of their mycelia within and part outside the roots.

Plant roots can also affect the organisms living in the soil. This subject has received very little study so far, but some information is available on the relation between the type of crop and wireworms.[3] Wireworms feed on the roots of most farm crops, but they cannot feed on flax or linseed roots. Beans, and perhaps peas, however, appear to excrete something into the soil that actually kills them, for A. C. Evans[4] at Rothamsted, found that a bean crop has a very powerful depressing effect on wireworm number—an effect not shown, for example, by linseed, whose roots are merely inedible to them.

Plants can also excrete inorganic cations and probably anions as well. This has been proved for potassium, calcium and phosphates (see p. 29 and p. 445) and probably ammonium,[5] and has been claimed for other ions, but with less satisfactory experimental evidence.

Plants can therefore affect the *p*H of the soil in which they are

[1] B. L. Hartwell, *J. Amer. Soc. Agron.*, 1927, **19**, 255, gives a summary of these results.
[2] See, for example, M. I. Timonin (*Soil Sci.*, 1941, **52**, 395), who used flax plants.
[3] See, for example, *Min. Agric. Bull.* 128, 1944.
[4] *Ann. Appl. Biol.*, 1944, **31**, 235.
[5] D. N. Prianischnikov, *Trans. 3rd Int. Congr. Soil Sci.*, Oxford, 1935, **1**, 207; *Ztschr. Pflanz. Düng.*, 1934, A **33**, 134.

growing by two well-proven means: excretion of carbon dioxide and differential uptake of anions and cations. Claims have been made that by these processes the plant can change the *p*H of its medium from one unfavourable to one more favourable for its growth,[1] but not enough work has yet been done on this subject to say how far this is a correct generalisation.

Plant roots can also have two physical effects in the soil. Some can bind soil particles together into strong and characteristic crumbs, and this is particularly marked with some grasses, an effect that has already been discussed on p. 418, and some roots are such strong growers that they can penetrate even quite compact subsoils, and hence a succession of such crops can improve the drainage or aeration of the subsoil. Lupins have been used in Germany to penetrate the hard pan underlying some of their sandy soils; lucerne and sweet clover have been used in irrigated regions to improve the drainage through a compact subsoil, and trees are sometimes used in the tropics for the same purpose, so reducing the amount of rain that runs off the soil surface and in consequence its erosive action.[2]

The Effect of a Crop on its Successor

Crops can influence their successors through the amount of water or available nutrients they leave behind in the soil and through their residues, which may be either beneficial or harmful. At one time various workers, such as de Candolle, assumed that plants could excrete toxins from their roots which remained in the soil for some time and which injured other plants of the same species, and that this was the reason why crops grew better in rotation than in continuous cropping. But C. G. B. Daubeny[3] at Oxford showed experimentally that this was not the correct explanation for the practice of crop rotation. He grew eighteen different crops continuously on the same plots, and compared the yields with those obtained when the same crops were shifted from one plot to another, so that no crop ever followed another of the same kind. No manure was supplied. The results showed a gradual decrease in the yield in almost every instance, and the decrease was generally greater when the crop was repeated year after year on the same plot than where it was shifted from one to another. Nevertheless, the difference between the yields in the two cases was not sufficient to justify any assumption of the existence of a toxin, except perhaps in the case of *Euphorbia lathyris*; in the other seventeen cases it was attributed to the more rapid removal from the continuous plots

[1] See, for example, A. Koslowska, *J. Ecol.*, 1934, **22**, 396; H. Kaserer, *Bodenk. PflErnähr.*, **21–22**, 1941, 697.

[2] For a short bibliography on this subject, see *Imp. Bur. Soil Sci., Tech. Comm.* 22, 1931.

[3] *Phil. Trans.*, 1845, p. 179.

of the mineral nutrients required by the plant. This explanation was supported by analyses of the plant ash and of the soil—analyses which led to the important distinction between "available" and "unavailable" plant food.

Farmers have, however, found by experience that crops grow better in rotation than in continuous succession. It is true that continuous cropping is possible: the Broadbalk wheat field at Rothamsted has already produced more than a hundred crops of wheat in succession with only a few fallows for weed control, and the Woburn Stackyard field produced more than fifty; but it is more difficult to secure good yields on Broadbalk than on Agdell Field, where wheat is grown only once in four-year rotation, other crops being taken in the intervening years (Table 114). But the cause of this benefit of the rotation is not due to the Broadbalk soil becoming "wheat-sick", though a quantitative explanation of the benefits of rotational cropping has not been worked out.

TABLE 114

Wheat Grown in Different Rotations but without Manure at Rothamsted

(1) Grown Continuously (2) in Alternation with Fallow
(3) in Four-course Rotation

Average for the year 1851 and every fourth year thereafter until 1927

Dressed grain in bushels per acre

Continuous wheat (Broadbalk, Plot 3)	Wheat after fallow (Hoosfield)	Rotation wheat (Agdell Field, Plot 5) formerly 21–22
11·3	14·0	24·0

The one group of crops that cannot be long grown continuously on the same piece of land are the legumes, and in particular clover and beans. Land continuously cropped to clover soon becomes clover-sick, and the lower the soil is in organic matter, the sooner clover-sickness sets in. The cause of this clover-sickness is almost certainly due to toxic substances produced by the clover roots: it or they can be destroyed by heating the soil when moist to 70° C., or by air-drying the soil in thin layers, and new clover plants can be protected from its toxic effects if large quantities of farmyard manure are added to the soil, but the toxic substance itself has not yet been isolated.[1]

The principal arable crop that affects its successors in English farming is clover: a one-year clover ley can improve the following crop

[1] These remarks apply to clover-sick Woburn soils. I am indebted to H. G. Thornton and H. H. Mann for these unpublished results.

very considerably due to the nitrogen it adds to the soil. This is shown in Table 115,[1] which gives the yield of wheat after fallow and after three different one-year leys from which either two hay cuts were taken or one hay cut and a bastard fallow. It also gives the nitrate nitrogen in the soil in the preceding October just after the second hay cut had been taken and just before the autumn rains had started to wash the nitrate into the subsoil. It shows that for the bastard fallow plots there is a general correlation between the nitrates in the soil surface in the autumn and the yield of wheat the following year.

TABLE 115

Effect of Type of Ley on Yield of Succeeding Wheat Crop

Rothamsted, 1933

Treatment in 1932	Fallow	Clover	Clover and rye-grass	Rye-grass
	Yield of wheat, grain in cwt. per acre			
One cut	30·6	25·5	21·4	18·1
Two cuts	—	25·1	18·9	13·8
	Nitrate nitrogen in p.p.m. in surface 20 cm. of soil: October 1932			
One cut	22·6	21·3	17·7	13·6
Two cuts	—	9·3	7·7	5·6

Under some conditions the benefit of a one-year's leguminous crop can be very large. Thus, T. B Noonan[2] has given an example from New South Wales where the yields of maize and oat hay when grown in a three-course rotation with red clover were 50 per cent higher than in a two-course rotation, as shown in Table 116.

TABLE 116

Benefit of Red Clover in Increasing the Yields of Subsequent Crops

	Two-course rotation Maize—oat hay		Three-course rotation Maize—oat hay—red clover	
	Total yield over 12 years, cwt. per acre	Yield per crop, cwt. per acre	Total yield over 12 years, cwt. per acre	Yield per crop, cwt. per acre
Maize	89·5	14·9	94·2	23·5
Oat hay	143·3	23·9	156·6	39·1
Red clover	—	—	4 grazing swards	18 months at 3 sheep per acre

[1] E. R. Orchard, unpublished Ph.D. Thesis, London.
[2] *Agric. Gaz. N.S.W.*, 1946, **56**, 527.

The residual effect of different legumes depends on the legume—a point which has already been discussed on p. 324, and Table 74 there gives some results obtained by T. L. Lyon in Cornell. These results showed that lucerne and clovers enriched the soil in nitrogen and benefited the succeeding crop markedly, whilst soybeans and beans taken for seed had little effect on the soil nitrogen and much less effect on the succeeding crop. And this result that annual leguminous crops taken for seed, such as beans, peas, soybeans and groundnuts, do not enrich the soil in nitrogen and do not have any appreciable beneficial residual effect on succeeding crops appears to be generally true under many conditions. Thus, A. E. V. Richardson and H. C. Gurney[1] found at the Waite Institute, Adelaide, that 1 cwt. per acre of sulphate of ammonia increased the yield of wheat following a corn crop by 7 bushels per acre, following a pea crop 6 bushels per acre, and it had no effect on wheat following a fallow. This result calls into question the current explanation of the English tradition that beans are an excellent preparation for wheat on heavy land. Most unfortunately no critical examination of the effect of a bean crop on the succeeding wheat crop has been made, and the only English experiment that the author is aware of which can give any information on this subject is an early one at Rothamsted on Agdell Field. This field is in a four-course rotation, three of the courses being wheat, swedes and barley, whilst the fourth is either beans and fallow, each on half of the field, or is clover and fallow, again each on half of the field, the clover coming on the same area as the beans. The design of the experiment is very bad, and the results of the clover-fallow comparisons are not consistent with all recent Rothamsted work, such as Table 115, for, as shown in Table 117, clover appears to be considerably better than fallow, provided enough mineral manures are given to ensure a good clover crop, and this beneficial effect appears to be quite marked three years after the clover has been ploughed in. Beans in this experiment also seem to be rather better than fallow for the succeeding crop, but they have no effect on the next two crops. Obviously these effects are sufficiently important, if they are genuine, to warrant a thorough examination of them, using modern experimental techniques.

The length of time the beneficial effects of clovers last in the land depends on many circumstances. As already mentioned in the previous paragraph, Rothamsted experiments in Agdell Field seem to imply that a clover crop yielding 3 tons per acre of hay is benefiting the land for at least three years, and the results of some Canadian rotation experiments in the moister regions of Ontario,[2] also suggest a one-year clover ley can benefit the second and possibly the third crop following

[1] *Emp. J. Expt. Agric.*, 1933, **1**, 193, 325. [2] P. O. Ripley, *Sci. Agric.*, 1941, **21**, 522.

TABLE 117

Residual Effects of Clover compared with Beans and Fallow over a Four-course Rotation

Agdell Field, Rothamsted

	Clover[1] hay cwt. per acre	Wheat grain bu. per acre	Swedes roots tons per acre	Barley grain bu. per acre	Beans[2] grain bu. per acre	Wheat grain bu. per acre	Swedes roots tons per acre	Barley grain bu. per acre
			Unma	nured				
Crop	19	24	0·5	15	15	26	0·9	27
Fallow	—	29	1·1	17	—	27	1·6	28
		Mineral f	ertilisers	only give	n to swe	des		
Crop	55	37	11	28	20	33	9	28
Fallow	—	35	9	19	—	31	9	26
	Mine	ral fertili	sers and	nitrogen	given to	swedes		
Crop	65	40	17	36	24	35	18	39
Fallow	—	35	18	28	—	33	19	38

it. But at the present time it is probably wiser to assume that the second and third year residual effects of even a good one-year clover ley are small. However, as W. B. Goldschmidt and E. R. Orchard[3] have shown, clovers can have an extensive root system which contains about the same concentration of nitrogen, phosphorus, calcium and potassium as the tops, and which can exceed the tops in weight. Hence, since the root system decomposes slowly in the soil, it will be releasing nitrogen and other nutrients over a long period. Clovers and the other pasture legumes differ from the annual seed legumes in having a much more extensive and heavier root system, and hence store in it a much higher proportion of the total nitrogen they fix; this may be the principal reason for the great difference in residual effects between them. Some old experiments at Rothamsted suggest that an old lucerne or clover ley will be benefiting corn crops for more than five years after it has been ploughed out,[4] and a recent ley experiment on the light land at Woburn[5] suggests that a three-year lucerne or grazed rye-grass–clover ley may affect the third crop after it has been ploughed out, as is shown in Table 118.

The residual effect of the ley, however, probably depends on the way it is managed, though this has received no investigation, for presumably a ley so grazed that clover is encouraged, particularly in the season

[1] Four courses beginning 1874–82–86–94.
[2] Six courses beginning 1854–62–70–78–90–98.
[3] *S. Africa Dept. Agric., Pamph.* 222, 1940.
[4] H. Nicol, *Emp. J. Expt. Agric.*, 1933, **1**, 22.
[5] *Rothamsted Exp. Sta. Rep.*, 1948.

TABLE 118

Residual Effect of Three Years' Ley or Three Years' Arable on the Succeeding Crops

Woburn (1941–8) *Plots receiving no dung*

Previous cropping .	3 year ley grazed	3 year lucerne cut for hay	3 year arable including 1 year seeds ley	3 year arable No seeds ley
First crop: Potatoes (mean of 8 crops, 1941–8), tons per acre	12·3	11·9	10·6	10·0
Second crop: Barley (mean of 7 crops, 1942–8), grain in cwt. per acre	17·4	20·5	16·2	17·8
Third crop: Potatoes (mean of 6 crops, 1943–8), tons per acre	11·2	9·9	9·6	9·8

before it is ploughed out, will leave a larger beneficial residue in the soil than one grazed to encourage the grasses.

In arid countries, different preceding crops can affect the yield of a succeeding one simply through the different amounts of water they leave in the soil. Thus, lucerne, by drying out a soil very thoroughly to a great depth, can affect a succeeding crop adversely compared with maize, which is a crop that cannot dry out a soil as thoroughly. This is illustrated in Table 119,[1] which gives the results of some Canadian experiments on the effect of various preceding crops on the yield of wheat, when the wheat crop is being limited by lack of water. Here lucerne is an undesirable, and maize a desirable crop, to precede wheat simply because their effects on the residual water in the soil are of more importance than on the nitrates.

Crops can, however, have a harmful effect on a succeeding crop if they leave residues behind that lock up soil nitrates on decomposition. A well-known example of this is the depressing effect a crop of sorghum can have on its successor. Thus, H. E. Myers and A. L. Hallsted[2]

[1] P. O. Ripley, *Sci. Agric.*, 1941, **21**, 522. He also gives the results for rotations in the more humid regions of Canada. For further examples of the complexity of predicting the response of wheat to lucerne and various grass leys when the leys affect both the nitrates and the soil moisture available to the succeeding crop, see *Canad. J. Res.*, 1939, **17** C, 212, 256. For results similar to the Alberta ones, but secured in Saskatoon, see M. Champlin and A. Wall, *Sci. Agric.*, 1947, **27**, 593.

[2] *Proc. Soil Sci. Soc. Amer.*, 1943, **7**, 316.

found that in a two-year rotation in Kansas, winter wheat yielded on the average 17 bushels per acre after maize, but only 11½ bushels per acre after kafir during the period 1918–41. J. P. Conrad[1] showed that this effect is due to the high sugar content in the crown roots of the sorghum; it was equivalent to nearly 2,000 p.p.m. of sucrose in the top foot of soil just under the plant and fell off to 15 to 20 p.p.m. 9 inches away. On the other hand, maize roots only returned the equivalent of 2 to 3 p.p.m. of sucrose to the soil. This depressing effect of the sorghum is therefore due both to the locking up of nitrates by the soil micro-organisms as they decompose this sugar, and also to the unfavourable soil structure that may ensue when these sugars are decomposing.[2] It can be rectified by adding nitrates to the soil, or, as Myers and Hallsted also showed, by taking a leguminous crop just before the sorghum.

TABLE 119

Effect of Preceding Crop on Yield of Wheat in Semi-arid Regions

3-year average, Lacombe, Alberta

Preceding Crop	Yield per acre	Yield of wheat in bushels per acre
Fallow . .	—	38·2
Maize . .	8·7 tons	34·6
Potatoes . .	6·0 tons	29·8
Lucerne . .	1·4 tons	23·6
Wheat . .	33·7 bushels	22·7
Grass ley . .	2·0 tons	21·8

Thus they found that, if oats followed sorghum grown after lucerne or sweet clover, there was enough nitrogen left in the soil from the lucerne or clover to provide for both the sorghum residues and the oats, but if soybeans was used as the leguminous crop, the sorghum residues depressed both the nitrate nitrogen content of the soil and the yield of oats to about one-third of their normal values, for soybeans do not enrich the soil appreciably with nitrogen.[3]

Crops can enrich the soil for other reasons than increasing the available nitrogen supply to successor crops. Thus, some crops have considerable power of extracting nutrients from compounds that are relatively unavailable to other crops, and accumulating these nutrients

[1] *J. Amer. Soc. Agron.*, 1927, **19**, 1091; 1937, **29**, 1014; 1938, **30**, 475.

[2] J. F. Breazeale, *J. Amer. Soc. Agron.*, 1924, **16**, 689.

[3] For further examples which show that soybeans taken as a grain crop do not enrich the soil in nitrogen, see R. E. Uhland, *Missouri Agric. Expt. Sta., Bull.* 279, 1930. For further references, see H. B. Brown, *Louisiana Agric. Expt. Sta., Bull.* 265, 1935; F. S. Wilkins and H. D. Hughes, *J. Amer. Soc. Agron.*, 1934, **26**, 901.

in their leaves. Such crops can be used in place of general or specific fertilisers, and for this reason they may have a very important function in primitive and subsistence agriculture where no money is available for buying fertilisers. Examples of this have already been given. Thus, lupins are very good extractors of phosphate (p. 461), and some plants accumulate minor elements such as zinc in their tissues (p. 51). G. H. G. Jones[1] has given an example of the leguminous shrub *Glycina javanica*, which in nine years on a poor soil in Kenya added 130 lb. of nitrogen annually, but also doubled the available phosphates in the top 9 inches of the soil as well as forming a litter very rich in phosphate and potash.

The Interaction between Plants Growing Together

Under natural conditions, plants always grow in association with those of other species: it is only in agriculture, and even then in the arable agriculture of the temperate regions, that the growing of pure stands of a single species of crop is traditional. Forests, prairies and even meadows and pastures more than a few years old always carry associations of many species of plants, and traditional cropping practices of the peasants in subtropical and tropical countries usually involve planting several species of plants on the same ground.[2]

Plants growing together, whether of the same or of different species, compete with one another both for space for their leaves above ground and for their roots below. Agricultural crops have naturally been selected through the ages for ability to withstand competition from other plants of the same species, though this is not true for many non-agricultural plants. Competition for light above ground is not always serious, as the leaves of many plants can synthesise carbohydrates in moderate shade. The factors involved in the competition for root space below ground have barely begun to be worked out yet. They include competition for nutrients and, in periods of drought, for water, but they may also include the roots of one plant excreting soluble compounds into the soil that inhibit the growth of roots of many other plant species in its neighbourhood.[3] This is probably the mechanism that reduces the interpenetration of the root system of neighbouring plants, for plants growing with neighbours close to them typically have a more compact root system than if their neighbours are more distant. These root-inhibiting substances are often somewhat specific, for in general the root system of a leguminous and a non-leguminous plant

[1] *E. Afric. Agric. J.*, 1942, **8**, 48.

[2] See H. Nicol, *Emp. J. Expt. Agric.*, 1935, **3**, 189, for an account of some of these practices.

[3] See, for example, S. U. Pickering and the Duke of Bedford, *Science and the Fruit Grower*, London, 1919; S. C. Varma, *Ann. Bot.*, 1938, **2**, 203; H. Oswald, *Vaxtodling*, 1947, **2**, 288.

growing in a mutually tolerated association may interpenetrate very readily.

S. C. Varma[1] further found that the harmful effects of root excretions were most marked when the plants are in the seedling stage, and this is the probable explanation of the observation so frequently made in the field, that even very small weeds can interfere with a germinating crop more than one would expect from their power of competing for light and nutrients. Hence, the great importance of keeping weeds in control during the early stages of crop growth.

The association of two crops growing together need not be harmful, particularly if their root systems tap different layers of the soil, or if the soil is well supplied with water or nutrients. In general, no annual crop has its yield per acre increased by being grown along with another, although the total yield per acre may be increased. But perennial crops, such as shrubs and trees, may have their yields increased when grown along with a companion crop, if the second crop occupies a different volume of soil and air, as, for example, ground-cover crops under orchards and tall shade trees over shrubs.

The associations of most importance in arable agriculture are those in which a leguminous plant is grown with a non-leguminous and those in which weeds grow with a crop; but two non-leguminous species are also sometimes planted together.

Taking two non-legumes simultaneously on the same piece of ground is an ancient practice, though it can hardly be used where the produce from each crop is to be sold separately. The old English maslin was a mixture of wheat and rye, and dredge corn is one of oats and barley, although peas or beans may be added to either. There is little doubt that this practice often enables higher yields to be obtained. Thus C. A. Zavitz,[2] working in Ontario, showed that provided one chooses varieties of oats and barley that come to maturity at the same time, the mixed crop of dredge corn gives a higher yield of grain per acre than that of either of the two components, averaging nearly 2 cwt. per acre above the higher yielding member of the pair. This benefit of growing two non-leguminous crops together can sometimes be seen when two legumes are grown together; thus, E. L. Worthen[3] found that a mixture of red clover and alsike gave a higher yield of hay than either separately: over an eleven-year period they gave annual hay crops of 21 and 19 cwt. respectively, compared with 27 cwt. for the

[1] *Ann. Bot.*, 1938, **2**, 203.

[2] *J. Amer. Soc. Agron.*, 1922, **14**, 225; *Ontario Dept. Agric., Bull.* 332, 1927. R. H. Morrish, *Michigan Agric. Expt. Sta., Spec. Bull.* 256, 1934, found the same result, but E. L. Worthen, *Cornell Agric. Expt. Sta., Bulls.* 748, 749, 1941, and E. Knudsen, *Tidskr. Planteavl*, 1947, **51**, 331, found no advantage in using dredge corn over the higher yielding member of the pair.

[3] *Cornell Agric. Expt. Sta., Bulls.* 748, 749, 1941.

mixture. He considered the reason was that the mixed crop covered the ground better than either alone.

The association of weeds with a crop is obviously of fundamental importance for all types of agriculture, and in this country alone weeds are responsible for a very considerable loss of yield on many farms. Weeds harm the crop by competing directly with it for light, water and nutrients, as well as sometimes by specific inhibitory effects on the crop's root system of the type already discussed. Under semi-arid conditions the main harmful effect of weeds is usually competition for water, which is particularly serious when, as often happens with maize, the weeds can extract more water from the soil than the crop. Under English conditions the main competition is for light if the weed is as tall or taller than the crop, and for soil nitrates.[1] In the latter case it is sometimes possible to neutralise any harmful effect of weeds simply by giving the crop a suitable dressing of sulphate of ammonia. Thus, sugar-beet can be grown almost unweeded without loss of yield on the light loam soil at Woburn if an adequate dressing of nitrogen is given, as shown in Table 120.[2] But this method of minimising the harm done by weeds, even if desirable, is not always possible, for it may happen that the weeds will be able to make better use of the added nutrient than the crop. T. Eden[3] has given an example of this in some Ceylon tea estates on phosphate-deficient soils: adding phosphate encourages some undesirable weeds more than the tea bushes, hence only the minimum quantity that will satisfy the requirements of the tea must be added.

TABLE 120

Effect of Weeds and Nitrogen on Yield of Sugar-beet at Woburn

Yield of washed beet in tons per acre

Sulphate of ammonia given in cwt. per acre	Crop kept		Reduction of yield due to weeds
	Weeded	Weedy	
0	11·68	9·45	2·23
4	15·47	15·43	0·04

These two examples are special cases of the general problem of the dependence of the competitive power of different plants on the soil

[1] G. E. Blackman and W. G. Templeman, *J. Agric. Sci.*, 1936, **26**, 368; 1938, **28**, 247; H. H. Mann and T. W. Barnes, *Ann. Appl. Biol.*, 1945, **32**, 15.

[2] Mean of years 1940, 1941, 1943. Results for the first two are given by E. W. Russell, B. A. Keen and H. H. Mann, *J. Agric. Sci.*, 1942, **32**, 330. F. Crowther (*Emp. J. Expt. Agric.*, 1943, **11**, 1) in the Gezirah found that cotton gave a larger response to nitrogen, derived from the previous year's fallow, when weedy than clean, in conformity with the above result at Woburn.

[3] With T. E. T. Bond, *Emp. J. Expt. Agric.*, 1945, **13**, 141.

fertility. This problem is of particular importance in grassland management, for here the principal methods available for controlling the composition of old pastures depend on manuring and grazing. The Rothamsted Grass Plots provide much information on the former;[1] they show that unmanured poor meadow land carries a very mixed herbage: very many species can grow, but they all grow badly. As soon as fertiliser is added, the extra nutrients encourage some species at the expense of others, so the number of species fall, though the hay yield usually rises.

The simple plant associations most commonly practised both by primitive and modern farmers is that of growing a leguminous and non-leguminous crop together. We have already discussed this association from the point of view of its nitrogen economy in Chapter 16. It was pointed out there that whilst much of the experimental data was consistent with the hypothesis that the non-legume could utilise nitrogenous compounds synthesised by the legume, yet it could equally well be interpreted as showing that the legume made no demands on the soil nitrates, and hence the reduced number of non-leguminous plants present in the association as compared with the pure crop, had a larger nitrogen supply to draw on.

The outstanding facts of the legume–non-legume association established on p. 321 are that in general the nitrogen content of the non-legume is higher[2] and of the legume lower than it would be if grown as a pure crop, and that neither crop gives as large a yield in mixed culture as when grown alone, although the combined yield may be higher than either. It also appears, as is shown in Table 121, that on the whole, the yield of the legume is usually more depressed in the association compared with the pure stand than is the cereal, but it is possible this is a property of the particular associations that have been studied.

In the tropics other associations besides grass or cereal are used with legumes. Thus, groundnuts and cotton go well together in Madras and Tanganyika, and several legumes go with the tropical root crops such as cassava. It is, in fact, possible that some of the most striking benefits of mixed cropping may be seen on the poorer soils of the humid tropics, but little exact information is available at present.

One other example of considerable practical importance of growing two crops together comes from orchard management, for under many circumstances it is profitable to have the ground between the trees

[1] The conclusions to be drawn from this experiment have been discussed by J. B. Lawes and J. H. Gilbert, *Phil. Trans.*, 1880, **171**, 289; 1882, **173**, 1181; 1900, **192** B, 139; W. E. Brenchley, *Manuring Grassland for Hay*, London, 1924.

[2] For examples of grasses growing with clover, see *Mississippi Agric. Expt. Sta., Bull.* 356, 1941, with Paspalum; D. B. Johnstone Wallace, *J. Amer. Soc. Agron.*, 1937, **29**, 441, and R. E. Wagner and H. L. Wilkins, ibid., 1947, **39**, 141, with temperate grasses.

TABLE 121

Effect of Mixed Cropping on Yield of Cereal and Legume

Yields of cereal and legume grain

Country and Association	Yield of cereal		Total	Yield of legume	
	Alone	With legume		With cereal	Alone
Ceylon:[1]					
In bushels per acre:					
Millet and beans	33	28	31	2·8	7·3
Greece[2]					
In cwt. per acre:					
Wheat and lentil, 1939	11·9	9·8	15·7	5·9	—
1940	7·4	6·6	9·3	2·7	7·3
Wheat and lupins, 1940	7·4	6·3	13·5	7·2	12·2
Ohio,[3] U.S.A.					
Maize and soybeans:					
Grain in cwt. per acre	28·6	24·2	27·8	3·6	10·9
Cut for silage:					
Green weight, tons per acre	8·7	7·7	10·1	2·4	8·1
Total digestible nutrients, lb. per acre	4380	3770	4620	850	2730
Total digestible proteins, lb. per acre	260	225	410	185	595

carrying a crop. The cover crop can have a number of different effects on the tree. If it is leguminous it can maintain the nitrogen supply to the tree. Cover crops also protect the surface of the soil, keeping it more permeable. They also can enrich the surface soil in minor elements such as zinc, for their root system may be deeper than that of the tree, and hence able to tap a larger volume of soil and in consequence collect a larger quantity of any minor element in short supply. They can also increase the carbon dioxide content in the soil air and perhaps for this reason reduce chlorosis troubles on calcareous soils.

[1] W. R. C. Paul and A. W. R. Joachim, *Trop. Agricst.*, 1941, **98**, 257. Crops were *Eleusine coracana* and *Phaseolus mungo*.

[2] J. S. Papadakis, *Ann. Gembloux*, 1939, **45**, 132; 1940, **46**, 1; *J. Amer. Soc. Agron.*, 1941, **33**, 504. The results given are the means for experiments conducted at six experiment stations. Lentil = *Ervum ervilia*.

[3] H. L. Borst and J. B. Park, *Ohio Agric. Expt. Sta., Bull.* 513, 1932. For a further example, giving the same result, see C. A. Mooers, *Tennessee Agric. Expt. Sta., Bull.* 137, 1927.

They can also reduce the loss of nitrate by leaching from the soil during the dormant season, and can be used to reduce the nitrate content in the soil at any period during the growing season, but for these two purposes in particular, their periods of growth may have to be very carefully chosen, otherwise they may be competing with the trees for water or nutrients. Thus, in England they are particularly liable to compete for nitrogen, and the techniques of cover-cropping and managing leys under trees must ensure that adequate nitrogen is available for the tree.[1]

[1] For a recent examination of the effects of cover crops on the growth and yield of apple trees in Kent orchards, see W. S. Rogers and Th. Raptopoulos, *J. Pomol.*, 1945, **21**, 120; 1946, **22**, 92, 103; with D. W. P. Greenham, ibid., 1948, **24**, 228, 271.

CHAPTER XXIX

THE WEATHERING OF ROCKS

Soils are derived from the decomposition of the mineral particles they contain and from the plant and animal remains added to them. The organic remains are usually being decomposed continuously and relatively rapidly by the soil organisms, and many of the mineral particles are also decomposing, but usually at a very much slower rate. The chemistry of these processes will be discussed in two parts: firstly, when the mineral particles are decomposing in the absence of organic matter, in which case the products of weathering remaining behind will be called a crust of weathering; and, secondly, when they are decomposing in the presence of organic compounds, when the process will be called soil formation.

Rocks and mineral particles can suffer physical disintegration without change of chemical constitution. Solid rock is broken down into smaller particles by many means. It may suffer grinding in or under ice sheets, and all the particles in boulder clays may have been produced by this action. It can be broken down into boulders by the expansive pressure of water in any cracks freezing into ice, or by plant roots trying to expand in restricted spaces; and these boulders can be made still smaller by being knocked on to other stones on the bottom of rapidly flowing mountain or desert streams. The solid rock surface can lose some of its constituent mineral grains due to their different coefficients of thermal expansion, for they will expand and contract by different amounts during the diurnal temperature changes of the surface, which can be very large in deserts. The rock can also lose mineral grains by water dissolving the cements which bind them together in the rock. The individual mineral grains can be reduced in size by the grinding action of ice and by abrasion in flowing water, as already mentioned, as well as by sand-blasting in the desert.

These finer particles produced by disintegration may then be carried away by wind, water or ice, and redeposited elsewhere as loess, alluvium or boulder clay. Or those on or near the surface of these deposits may be carried into lower layers with the percolating water.

The mineral particles can also suffer chemical decomposition through the solvent action of the water itself, and through the reactions between the dissolved or suspended substances in the water, as, for example, oxygen, carbon dioxide, alkalis and organic acids, and the surfaces of the particles. Some of these reactions can occur at depths of 30 feet

or more below the soil surface, so clearly are of importance in forming the crust of weathering, whilst the effect of organic acids, and possibly of alkalis also, is only of importance near the surface and hence in the soil forming processes.

The fate of the products of decomposition depends mainly on the rate of water movement through the soil: the greater the amount of downward leaching the higher the proportion of the products of weathering that are removed from the zone in which they were formed and either redeposited in lower layers of the soil or else carried with the percolating water into the ground-water and thus into the rivers. Water movement is not the only agency causing movement of the products of weathering. Plants growing on the soil counteract some of the downward movement brought about by the percolating water, for their roots absorb some of the products of weathering from the subsoil and transfer them to their leaves and stems, which later fall to the ground and decompose, releasing these products of weathering in the surface soil. Burrowing animals, such as earthworms, termites and some rodents, also affect the distribution of the products of weathering consequent upon the mixing of soil from different layers which they bring about.

The Formation of the Crust of Weathering

As rain-water percolates through the soil it loses some of its dissolved oxygen and becomes enriched in carbon dioxide. This water causes three groups of reactions to take place on the surface of mineral particles over which it moves: hydration, oxidation and hydrolysis. The mineral surface takes up water molecules to form more hydrated minerals; all ferrous and sulphide ions become oxidised; and ions split off from the surface of the crystal lattices under the influence of the carbonic acid. The speed of these decompositions depends on the constitution of the mineral particles concerned, but increases with the temperature and the quantity of the percolating water.

The exact chemistry of these decompositions has not been worked out. Thus, neither the way in which water molecules become added to the ions forming the mineral lattice, nor the actual ions that split off the mineral lattice are always known in detail. Again, an acid clay particle close to a mineral particle appears to be a more powerful extractor of cations from the mineral than is carbonated water itself, so acid clays may act as weak catalysts in the hydrolysis of mineral particles.[1]

Rock particles do not all decompose uniformly easily. Small particles, by virtue of their increased surface area for a given weight of material,

[1] E. R. Graham, *Soil Sci.*, 1940, **49**, 277; 1941, **52**, 291.

decompose more easily than larger ones. Among the common primary minerals, the ferro-magnesian weather comparatively easily, olivine usually weathering more easily than augite or horneblende. The calcium-rich plagioclase felspars weather more easily than the sodium-rich, and both weather easier than the potash felspars. Of these the orthoclase tends to weather quicker than microcline, which is relatively resistant to decomposition. The biotite micas tend to weather more easily, and the muscovite micas more slowly, than orthoclase.[1] Quartz and some heavy minerals, such as zircon, tourmaline and some of the titanium minerals, are very resistant to weathering and decompose only slowly under conditions very favourable for the decomposition of the other minerals.[2]

The process of weathering involves two stages: the hydrolysis of the minerals and the disposal of the products of hydrolysis. Some products are very soluble in the soil water, for example, chlorides and sulphates, and as fast as these are produced by hydrolysis they appear in the soil solution and move with it. Other products, such as the principal cations sodium, potassium, magnesium and calcium, can be held as exchangeable bases on being set free, and they are relatively easily removed if the soil is subject to much leaching. Soluble silica is also produced and may move out of the soil. Finally, certain products, such as hydrated iron and aluminium oxides, tend to accumulate in the crust of weathering as the other elements are removed.[3]

These stages in the process of weathering of rocks can be seen from the analysis of the products of weathering of igneous rocks within the crust of weathering. Table 122 gives the analysis of three similar rocks and of their weathering products for conditions of slow weathering in Massachusetts, of moderate weathering in Virginia and rapid weathering in British Guiana. The table also gives the percentage loss of each constituent on the assumption that no aluminium in two cases, or iron in the third, has been lost from the soil.

This assumption is not quite accurate, as small amounts of iron and aluminium are found in the drainage waters,[4] so that the percentage loss of constituents of the rock given in the last column of the table is certainly an under-estimate. In these examples one can see how the hydration of the products of weathering increases, how the bases are removed

[1] See, for example, S. S. Goldrich, *J. Geol.*, 1938, **46**, 17; F. J. Pettijohn, *J. Geol.*, 1941, **49**, 610.

[2] See, for example, F. J. Pettijohn and also F. Smithson, *Geol. Mag.*, 1941, **68**, 97.

[3] For a further discussion of this aspect, see B. B. Polynov, *The Cycle of Weathering*, trans. A. Muir, London, 1937.

[4] A. Demolon and E. Bastisse (*C.R.*, 1944, **219**, 293) have given analyses of the aluminium, iron and silicon contents of water that has percolated through 60 cm. of soil. See also J. S. Joffe, *Soil Sci.*, 1940, **50**, 57, and *Proc. Soil Sci. Soc. Amer.*, 1941, **5**, 187, for other examples. C. S. Howard, *Trans. Amer. Geophys. Union*, 1948, **29**, 375, 379, has given the iron and aluminium contents of the Colorado River and other rivers in the north-west of the U.S.A.

very strongly under moderate weathering, how the silicon is lost more slowly than the bases, and how the loss of iron does not seem to depend very much on the conditions of weathering.

The relative resistance of iron and aluminium to removal during weathering is not always as given in Table 122. Sometimes more

TABLE 122

The Different Rates of Removal of Constituents from Basic Rocks during Weathering

	Diabase from Massachusetts[1]			Diorite from Virginia[1]		
	Fresh rock	Crust of weathering	Per cent loss of constituent	Fresh rock	Crust of weathering	Per cent loss of constituent
Al_2O_3	20·2	23·2	standard	17·6	25·5	standard
Fe_2O_3	3·7	12·7	18·1	16·8	19·2	21·0
FeO	8·9	0·0				
SiO_2	47·3	44·4	18·0	46·7	42·4	37·0
MgO	3·2	2·8	21·7	5·1	0·2	97·0
CaO	7·1	6·0	25·9	9·5	0·4	97·0
Na_2O	3·9	3·9	12·8	2·6	0·6	85·0
K_2O	2·2	1·7	29·1	0·5	0·5	39·0
Loss on ignition	2·7	3·7	—	0·9	10·9	—
Per cent of rock lost	—	—	14·9	—	—	37·5

	Dolerite from British Guiana[2]		
	Fresh rock	Crust of weathering	Per cent loss of each constituent
Al_2O_3	15·2	26·9	12·3
Fe_2O_3	3·1	27·9	standard
FeO	11·2	3·1	
Quartz	1·6	13·2	82·0
Combined SiO_2	49·7	7·9	
MgO	5·6	0·7	94·0
CaO	9·6	0·5	97·0
Na_2O	2·1	0·8	82·0
K_2O	0·6	0·3	73·0
Loss on ignition	0·3	17·3	50·6
Per cent of rock lost	—	—	49·5

[1] G. P. Merrill, *Rocks, Rock-Weathering and Soils*, New York, 1897. These are also given in F. W. Clarke, *Data of Geochemistry, U.S. Geol. Surv., Bull.* 770, 1924.

[2] J. B. Harrison, *The Katamorphism of Igneous Rocks Under Humid Tropical Conditions*, Harpenden, 1934.

iron than aluminium is removed from the crust of weathering, and sometimes titanium is the least mobile.[1] Thus, in the weathering of an amphibolite in Georgia, U.S.A., if one assumes the iron has all remained in the crust of weathering, then 57 per cent of the silicon, 40 per cent of the aluminium, and 11 per cent of the titanium have been removed.[2]

Some of the products of weathering move with the percolating water into the ground-water and thus into rivers. Hence, analyses of the dissolved salts in rivers emerging from catchment areas on a definite rock type would give valuable information on the rate of weathering *in situ*, provided the analyses were made at a number of times during the year and the river was gauged, that is, its flow measured. Unfortunately, data of this type do not seem to have been collected. However, F. W. Clarke[3] has tabulated many analyses of the salts in large rivers and, assuming that these analyses are typical for the average salt content throughout the year, has calculated the average rate of removal of the soluble products produced by weathering over large catchment areas. Thus, European and North American rivers carry away salts at the rate of 100 tons of soluble inorganic substances per square mile of their catchment area per year, which corresponds to the solution of one foot of soil in about 20,000 to 30,000 years, whilst tropical rivers, owing to the much higher transpiration of the vegetation growing in their catchment areas, only carry away about 50 tons per square mile per year. The actual weight of the soluble constituents so removed, converted into the more convenient units of pounds per acre per year, are approximately as follows:

	CO_3	SO_4	Cl	NO_3	Ca	Mg	Na	K	$Al_2O_3+Fe_2O_3$	Si
N. American and European rivers	130	49	17	3·5	73	12	21	8	54	15
Amazon	57	15	10	1·1	33	4·5	9	4	10	16
Drainage water, Broadbalk, continuous wheat, unmanured plot[5]	—	56	24	152	159	7	10	3	13	12

Thus, in spite of the fact that the Amazon only carries half as much salts per square mile of catchment area as the temperate rivers, yet it carries away as much silicon and twice as much iron and aluminium per square mile. This result is naturally a corollary of the results given in

[1] For an example on the Hawaiian lavas, see G. J. Hough, P. L. Gile and Z. C. Foster, *U.S. Dept. Agric., Tech. Bull.* 752, 1941.

[2] L. T. Alexander, S. B. Hendricks and G. T. Faust, *Proc. Soil Sci. Soc. Amer.*, 1941, **6**, 52.

[3] *Data of Geochemistry.*

[4] Iron and aluminium not separately determined. However, C. S. Howard, *Trans. Amer. Geophys. Union*, 1948, **29**, 375, finds the iron content of the waters of rivers in the western states of the U.S.A. to be only between 1 and 5 per cent of their silicon contents.

[5] Calculated from the mean of five samples analysed by A. Voelcker, *J. Chem. Soc.*, 1871, **24**, 276.

Table 122, and the previous paragraphs, for the course of decomposition under intense, as compared with mild, weathering. Under humid tropical conditions when basic igneous rocks are being weathered, the rate of decomposition can be much higher than is indicated in this table. Thus, H. W. van der Marel[1] found that biotite and albite-anorthite rich rocks weather rapidly enough to liberate over 200 to 250 lb. per acre of potassium. Under the cool temperate conditions of Versailles broken granite, in a lysimeter only 60 cm. (about 2 ft.) deep, loses silicon at the annual rate of 17 lb. per acre and calcium at 110 lb. per acre.[2]

Not all the soluble products of weathering are immediately transported into the ground-water and the rivers: some are reprecipitated lower down in the soil and some recombine, either where they have been produced, or lower down in the soil, to form secondary minerals, such as clays, that are resistant to weathering. Thus calcium carbonate and sulphate dissolved from the surface soil are often precipitated in the subsoil, particularly when the rainfall is so low that little water penetrates beyond the root range of the plants.

The factors controlling the type of clay mineral synthesised, and its rate of formation, under different field conditions have not yet been studied intensively. The general rule appears to be that montmorillonitic clays are produced in the presence of a good, and kaolinitic of a poor, base supply.[3] Thus montmorillonitic clays are usually found in areas of poor drainage, which ensures a good base supply, and warm climates, which ensures that weathering will be active enough to produce a good supply of silica and hydrated iron and aluminium oxides. Whether or not the ferrous iron, which is also produced under these conditions, plays a fundamental role in this synthesis is still undecided. The montmorillonitic clays so produced become increasingly mixed with illite-like clays as the proportion of aluminium in 4-co-ordination increases, that is, as the clay becomes more beidellite-like. Kaolinite clays are formed under conditions of a low concentration of bases, that is, in well-drained areas, though as the base status at the site of synthesis rises, so illite-like clays tend to be formed along with the kaolinite. The illite clays thus form the intermediate group between the pure kaolinites of strongly leached, low base soils and the pure montmorillonites of the poorly drained, high base soils.

[1] *Soil Sci.*, 1947, **64**, 445. [2] A. Demolon and E. Bastisse, *Soil Sci.*, 1938, **46**, 1.

[3] For examples from Australia, see J. S. Hoskings, *Aust. J. Counc. Sci. Indust. Res.*, 1940, **13**, 206; from India, G. Nagelschmidt, A. D. Desai and A. Muir, *J. Agric. Sci.*, 1940, **30**, 639; from Russia, I. D. Sedletsky, *Pedology*, 1942, Nos. 3–4, 61. For a recent discussion, see G. Nagelschmidt, *Imp. Bur. Soil Sci., Tech. Comm.* 42, 1944; C. S. Ross and S. B. Hendricks, *U.S. Geol. Survey, Prof. Paper* 205 B, 1945.

Illitic clays are also produced directly from micas and perhaps felspars as well. D. M. C. MacEwan[1] has been able to follow the transition of a biotite through hydrobiotite or vermiculite into an illite, a process in which it is not necessary to assume that the basic lattice has been completely broken up.

The silica and the iron and aluminium hydroxides taking part in the clay synthesis do not need to be produced at the same place, for silica-rich water, leaching through the aluminium hydroxide left behind as a residual product in the crust of weathering, can convert it into kaolinite. Thus, J. B. Harrison,[2] working in British Guiana, F. Hardy and G. Rodrigues[3] in Trinidad, and L. T. Alexander and his co-workers[4] in the south-eastern States of the U.S.A., found that the gibbsite produced in the crust of weathering of basic igneous rocks becomes converted into kaolinite by this means.

The effect of the climate on the rate of formation of clay and on its composition depends on the amount and the temperature of the percolating water. The greater the amount of water and the higher its temperature the greater is its power of decomposing rock minerals, the more rapid is the formation of clay, and the lower is its silicon content, that is, the higher the ratio of kaolinitic to illitic clay formed.

The quantitative relationships between the rate of clay formation and its composition with such fundamental quantities have not yet been worked out. What has been done is to make very crude estimates of the two primary variables—the absolute amount and the temperature of the percolating water—and to look for correlations between them and the amount and composition of the clay in the soil over areas where the parent material is reasonably similar. The approximations that have usually been made are to replace the temperature of the percolating water by the mean annual temperature, and to estimate the amount of percolating water from some very inexact assumptions connecting it with the mean annual rainfall and either the mean annual temperature or moisture saturation deficit of the air.[5]

H. Jenny[6] has used this type of method to show how the amount of clay in soils derived from granite and gneisses in the United States increases with temperature and percolation. Little clay is formed unless the mean annual temperature is above 5° C., and appreciable amounts are only formed when it exceeds 10° C. Again, E. M. Crowther[7]

[1] *Verre et Silic. Indust.*, 1948, **13**, 41. See also G. F. Walker, *Miner. Mag.*, 1949, **28**, 693.
[2] *The Katamorphism of Igneous Rocks Under Humid Tropical Conditions.*
[3] *Soil Sci.*, 1939, **48**, 361.
[4] L. T. Alexander, S. B. Hendricks and G. T. Faust, *Proc. Soil Sci. Soc. Amer.*, 1941, **6**, 52.
[5] For a discussion on these methods, see H. Jenny, *Factors of Soil Formation*, New York, 1941.
[6] *Soil Sci.*, 1935, **40**, 111.
[7] *Proc. Roy. Soc.*, 1930, **107** B, 1.

and others[1] have shown that the silicon-aluminium ratio in clays decreases as the rainfall increases. But the effect of temperature has not yet been unequivocally demonstrated. Thus, using the same data but different methods of computing the amount of rainfall that percolates to the ground-water, Robinson and Holmes concluded that, for constant amount of percolation, the silicon-aluminium ratio of the clay decreases with increasing temperature, whilst Crowther concluded it had no influence—a conclusion difficult to justify on physico-chemical grounds, but probably due to the method of estimating the amount of percolation being unsatisfactory.

B. B. Polynov[2] has pictured the process of the formation of a crust of weathering from parent rock occurring in four stages, each characterised by a typical accumulation product. The first stage involves the loss of all readily soluble products of weathering, such as chlorides and sulphates, and the accumulation of calcium carbonate precipitated some depth below the surface, and often of calcium sulphate, as gypsum, at a greater depth. The second stage involves the washing out of the calcium carbonate and the formation of clay under neutral conditions; that is, the accumulation of beidellitic and illitic clays. The third stage involves the washing out of the exchangeable bases, so the clay becomes acid and weathers to kaolinitic clays which accumulate, whilst the fourth stage involves strong removal of silicon and the accumulation of meta-halloysite,[3] bauxites and haematites. This stage is only developed under conditions of long-continued leaching under tropical conditions, conditions which also give very deep crusts of weathering.

Laterites and Ferrallites

These processes of rock weathering and mineral synthesis are very clearly displayed in the tropics, for these regions contain many old peneplains that have been subjected to weathering for very long periods with little disturbance. Further, weathering proceeds much more vigorously there, for the soil temperatures are much higher than in the temperate zone. Vageler states that in the regions lying between latitudes 20° N. and 20° S. the soil temperature at a depth of 1·5 metres is nearly constant throughout the year at between 25° and 26° C., whilst in

[1] For example, W. O. Robinson and R. S. Holmes, *U.S. Dept. Agric., Bull.* 1311, 1924; I. C. Brown and H. G. Byers, *U.S. Dept. Agric., Tech. Bull.* 609, 1938; H. B. Vanderford and W. A. Albrecht, *Missouri Agric. Expt. Sta., Res. Bull.* 345, 1942; S. P. Raychaudhuri and J. N. Chakravorty, *Indian J. Agric. Sci.*, 1943, **13**, 252.

[2] *The Cycle of Weathering*, trans. A. Muir, London, 1937.

[3] I. D. Sedletsky (*Pedology*, 1942, Nos. 3–4, 61) has pointed out that meta-halloysite, and not bauxite, as assumed by Polynov, is the probable product of accumulation from the weathering of kaolinite.

England the mean temperature at this depth is about 10° C. Thus, these weathering processes have produced crusts of weathering over 60 feet thick in places from solid rock. Studies of weathering are particularly profitable in many of these regions as the parent rock is primary crystalline rock and not merely residual products of weathering of previous geological periods.

Two different types of primary crusts of weathering are produced from igneous rocks: those giving aluminium hydroxide residual products or bauxites, and those giving kaolinites, the former being characteristic of basic and the latter of acidic igneous rocks. There is no generally accepted evidence that kaolinites ever lose their silicon by weathering leaving aluminium hydroxides behind as their residual products of accumulation. This division between bauxitic and kaolinitic residual products depends on the weathering of the individual mineral particles in the rocks, and as there is an assortment of different minerals, so it is possible to have bauxites and kaolinites being formed from the same rock.

The actual forms of the residual products of weathering appear to be as follows. The kaolinites are probably present as halloysites; free silica recrystallises as quartz, opal or chalcedony; the aluminium is present mainly as gibbsite or hydrargillite, although böhmite γ-AlO(OH) and diaspore α-AlO(OH) may also be present; and the iron is present mainly as limonite FeO(OH) and haematite Fe_2O_3, but some may be present as magnetite remaining from the original minerals, and some combined with titanium as ilmenite. No iron silicates have yet been isolated or recognised in these crusts of weathering, though F. Hardy and G. Rodrigues[1] considered they had evidence for an iron silicate of composition $2Fe_2O_3 . SiO_2 . 2H_2O$, which corresponds to no known mineral. However, a high proportion of the iron present can usually be brought into solution by Truog's or Tamm's method, and it is possible that if the material was thoroughly treated with Tamm's acid oxalate using Schofield's technique (see p. 114), most of the iron would come into solution, but this point has not yet been established.

There are probably all transitions between the two extreme types of crust of weathering—the kaolinitic and the ferruginous bauxite—and they give soil material having colours ranging from almost pure white or very light yellow or brown, through brown to red of varying intensities to almost purple. The individual particles are all small, mainly in the fine silt and clay fractions, as they are all secondary products of weathering, but they are cemented together into larger particles—sometimes called pseudo-sand because they act as sand particles—by iron oxide cements and possibly aluminium and silicon hydroxides also, although

[1] *Soil Sci.*, 1939, **48**, 483.

this has not yet been definitely proved. Hence, these soils do not show the general properties of clays: they are not plastic, do not swell on wetting, are permeable, have a very low base exchange capacity, and are easy to cultivate. When the material is red the soil is often called a tropical red earth or loam, and when the amount of kaolinite present is low it has been called a laterite, but for reasons to be discussed shortly, it will be called a ferrallite instead, a name used by G. W. Robinson[1] in the third edition of his book. Ferrallites are only formed from the weathering of basic igneous rocks on well-drained sites, and are only deeply developed on ancient peneplains, which are fairly level and extensive land surfaces. They are not formed if the crust of weathering is subjected to strong ground-water influences, for ground-water nearly always contains water-soluble silica, which reacts with the aluminium hydroxide to form kaolinitic clays, as already described on p. 504.

The word laterite, which has been so extensively used by pedologists, was first coined by F. Buchanan,[2] a geologist, in 1807 for a reddish to yellow material with a typical vermicular structure, which is as soft as cheese when freshly exposed, but which hardens on exposure to air. It is extensively used in India as a building stone, and Buchanan coined the word laterite from the Latin word *Later*—a brick, from this use. In Malabar it is derived from acid igneous rocks such as granites and gneisses; is somewhat similar to what a geologist calls a lithomarge, contains between 30 and 50 per cent of kaolinite with 15 to 40 per cent of iron oxides, sometimes a little free aluminium hydroxides, and some quartz and unweathered felspars; and it may have been formed under an indurated iron pan, but if it was the pan has disappeared. The cause of the hardening on exposure to air has not been established, though it is probably due in some way to the dehydration of some of the hydrated iron oxides present.

The word laterite is, however, used by the geologists in a different sense from Buchanan's.[3] For them it is an indurated ferruginous crust or hard pan, most typically lateritic when it contains mainly bauxite and hydrated iron oxides. Hence in constitution it approaches the ferrallites described above, but it is a hard crust, not a friable earth, having either a pisolitic or vermicular structure. A pisolitic laterite

[1] *Soils; Their Origin, Constitution and Classification*, 3rd ed., London, 1949. C. E. Kellogg (*Commonw. Bur. Soil Sci., Tech. Comm.* 46, 1949, and *Publ. I.N.E.A.C. Ser. Sci.* 46, 1949) has introduced the name Latosol for leached red and yellow tropical soils.

[2] *A Journey from Madras through the Countries of Mysore, Canara and Malabar*, 3 vols., London, 1807. C. S. Fox revisited Buchanan's original sites in 1933 and published his observations in *Rec. Geol. Surv. India*, 1936, **69**, 389. This publication quotes the relevant entries from Buchanan's book and gives some chemical analyses of the type material, and has been freely drawn upon in the above paragraph.

[3] See, for example, J. M. Campbell, *Mining Mag.* (*London*), 1917, **17**, 67, 120, 171, 220, and C. S. Fox, *Mem. Geol. Surv. India*, 1923, **48**, 221, who gives an extensive bibliography on the subject.

contains spherical masses of soil material cemented together with hydrated iron oxides, formed at approximately equal distances apart, in a porous clay matrix. These special masses grow outwards until they touch each other, but the spaces between the masses never fill up completely, so the whole always remains porous. These particles vary in size between 3 and 10 millimetres, and if these particles are not strongly cemented together, the material is often known as pea iron gravel in Africa. The vermicular, or as it is sometimes called, vesicular laterite, is more solidly indurated with iron and perhaps aluminium oxides and hydroxides, but contains many tortuous channels through this ironstone, which are often filled with a light-coloured bauxite, kaolinite or quartz. The reason for these two different types of laterite is not known, but it is possible that the vesicular is brought about in some way by termite activity.[1]

This type of laterite is only found in regions of fluctuating ground-water, and it is formed near the highest level the ground-water reaches. It is for this reason often called a ground-water laterite in soil literature. The zone through which the ground-water level fluctuates may be as thick as 50 feet, as, for example, in parts of India having a high monsoon rainfall, and a proportion of the iron it originally contained has been moved out from it into the laterite horizons above; but this removal and deposition takes place unevenly, for the zone is streaked with red or reddish colours on a white to grey background.

There are several descriptions of laterites in the geological and pedological literature which are considered to be Buchanan laterites. The author unfortunately has not visited Malabar, so has not seen the type area, but he was able to visit a laterite quarry in Malacca in 1949. This laterite has been described by J. B. Scrivenor,[2] who quotes T. J. Newbold's opinion that it was the same material as occurs in Malabar. Yet this laterite appeared to be a pea iron gravel. He could not see what underlay this laterite in the quarry where it was worked, but close by in another quarry was a vermicular laterite, which was being quarried for road metal. Further, the pisolitic and vermicular laterites described by R. L. Pendleton and S. Sharasuvana[3] as used for building stone in Siam, two of whose photographs are reproduced in Plates XXVIII and XXIX, appear to be the laterite of the geologists rather than Buchanan. It is possible therefore that Newbold in Malabar mistook the laterite crust overlying the lithomarge for the Buchanan laterite.

[1] I am indebted to Dr. R. L. Pendleton for drawing my attention to this possibility.

[2] J. B. Scrivenor, *The Geology of Malaya*, London, 1931, who quotes a description of this material given by T. J. Newbold, *British Settlements in Malacca*, Vol. I, 1839, who states that this laterite is the same as Buchanan's on the Malabar coast.

[3] *Soil Sci.*, 1942, **54**, 1; 1946, **52**, 423. For a description of what appears to be similar material in Ceylon, locally known as Cabook, see A. W. R. Joachim and S. Kandiah, *Trop. Agricst.*, 1941, **96**, 67.

Soil science, therefore, has to deal with three laterites. There is the ground-water laterite, which possesses a horizon indurated with iron, and containing in addition quartz, kaolinite or bauxite, depending on the parent material and drainage conditions. It may be very thick and can be formed on any parent material containing sufficient iron compounds. Then there is the deep red soil, rich in iron and aluminium hydrated oxides and low in kaolinite, and therefore possessing a low silica-sesquioxide ratio, which is only formed on basic igneous rocks under conditions of good to moderately good drainage, and is only deep on old peneplains. But these soils usually occur in regions of high, or seasonally high rainfall, so they nearly always show signs of impeded drainage in their subsoil. This characteristically causes a horizon containing small pea iron gravel concretions, whose concentration increases with increasing amount of impedance in the drainage, which overlies a deep reticulately mottled red to whitish layer becoming whiter with depth due to the increasingly complete removal upwards of the iron initially present in it. The white material is mainly kaolinitic clay formed by the re-silication of the aluminium hydroxides in the groundwater. The reticulately mottled zone is probably Buchanan's laterite, often only weakly developed, for it dries out to hard lumps very resistant to weathering, and for this reason it is most important to prevent the surface of eroded red soils of this type ever being exposed to the sun during dry weather. P. E. Vageler,[1] H. Erhart[2] and E. C. J. Mohr[3] all give coloured plates illustrating this type of soil in their books.

Weathering in the Soil Zone

So far we have only been concerned with the weathering brought about by the percolating water containing dissolved oxygen and carbon dioxide, and this weathering can take place from the surface downwards to considerable depths. But this is not the only process of weathering taking place in the superficial layers of the soil. In the first place, the roots of some plants can hydrolyse some of the minerals they come in contact with, removing more of certain nutrients, such as phosphates and possibly also potassium, from the surface of the particles than can the bicarbonate in the soil solution. In the second place, organic matter derived from the vegetation is being decomposed by the soil organisms, and both the process itself, and the products of the decomposition, will affect the weathering. In the third place, plant roots are continually removing nutrients and other products of weathering from the root

[1] *Grundriss der tropischen und subtropischen Boden*, 2nd ed., Berlin, 1938, 1st ed. translated by H. Greene, *An Introduction to Tropical Soils*, London, 1933.
[2] *Traité der Pédologie*, 2 vols., Strasbourg, 1935 and 1937.
[3] *De Bodem der Tropen in het Algemeen*, Vol. I, Part 2, Amsterdam, 1933.

zone and incorporating them in their aerial tissues, which fall on to the soil surface at death. Thus, natural vegetation produces a continuous circulation of certain substances in the surface soil and so counteracts to some extent their washing out in the downward percolating water.

There are not a great many reliable figures to indicate the magnitude of this annual return of nutrients under natural conditions. One can, however, make some estimates that must be treated with caution. Thus, in Table 113, on p. 483, meadow hay, giving 1½-ton crop per acre, which is not a heavy crop, has an ash content of 200 lb. per acre, and this contains about 27 lb. of silicon, about 80 lb. of cations, and probably only a few pounds of iron and aluminium. Natural prairies would probably return at least this quantity of minerals every year whenever the rainfall permitted reasonable growth. Forests also seem to return about 200 to 300 lb. per acre of minerals to the soil each year in their leaf fall,[1] but the proportion of cations to silicon in the dead leaves appears to vary between wide limits. E. Wolff,[2] in 1871 and 1880, collected together many ash analyses of forest leaves and litter and found silicon contents varying from 5 to 35 per cent, corresponding to silica content about double this, with 10 to 20 per cent being a common range. The few more recent determinations available all indicate great variability in silicon content, the causes of which have not been analysed out. Returns of up to 50 lb. per acre of silicon, and 55 lb. per acre of calcium are probably not uncommon under hardwood forests, whilst under coniferous forest the annual return of calcium may be under 25 lb. per acre, and probably considerably less than this on very acid soils. The annual silicon return under these conditions is very variable. The amount of iron and aluminium returned is probably under 2 per cent of the total minerals, but these figures are again uncertain, particularly those for aluminium.

It is interesting to compare these figures of annual circulation of calcium and silicon with the amounts carried away by rivers, given on p. 502. Over catchment areas as a whole it appears that the average loss of calcium per year into rivers is of the same order of magnitude as the amount in circulation, but the loss of silicon is probably only about a half of that in annual circulation.

Living organisms have two direct effects on the weathering of the mineral particles in the soil zone. In the first place, they respire carbon

[1] The figures quoted here and lower down have been derived in part from the following papers: R. R. McKibbin and L. I. Pugsley, *McGill Univ., Tech. Bull.* 6, 1930; F. J. Alway *et al.*, *Soil Sci.*, 1933, **36**, 399; H. A. Lunt, *Connecticut Agric. Expt. Sta., Bull.* 394, 1937; *Bull.* 449, 1941; R. F. Chandler, *J. Amer. Soc. Agron.*, 1941, **33**, 859; *Proc. Soil Sci. Soc. Amer.*, 1944, **8**, 409; *Cornell Agric. Expt. Sta., Mem.* 228, 1939; S. Lindberg and H. Nonming, *Svenska SkogsvFören. Tidskr.*, 1943, **41**, 353.

[2] *Aschen Analysen*, Berlin, Vol. I, 1871, and II, 1880.

dioxide and take up bases, and hence by acting as centres of powerful base extraction, cause the residual mineral to weather more easily. Secondly, they may excrete acids capable of bringing into solution compounds which are relatively insoluble in carbonic acid solutions. Thus, as will be discussed in more detail on p. 521, organic acids such as oxalic, tartaric and citric, which can disperse iron and aluminium hydroxides relatively easily, may sometimes be produced by micro-organisms in the soil.

The decomposition of the organic matter can also influence the products of weathering formed, for as it decomposes so the minerals it contains, such as the bases and silica, are released in soluble, and hence in mobile and reactive forms. In particular, the continuous release of mobile silica will encourage clay formation in the lower parts of the soil zone. Thus the root zone of a soil is a zone in which soluble products of weathering are in circulation on the one hand, but in which the weathering processes are proceeding more actively than in the deeper subsoil.

The plant remains can be given back to the soil in three ways. They can be returned to the surface of the soil and only the soluble products of decomposition wash down into it; they can be returned to the surface, but mixed with the superficial layer of the soil by earthworms and other animals; and they can be returned to the soil in the root system of the plant. In so far as any one of these methods is much more important at a particular site than the other two, so the type of soil that develops there is characteristic of this method of plant debris return. But since all three methods are usually operative to a greater or less extent at every site, these characteristic soil types tend to be models which any particular soil can be compared with. In fact the first method of return is often dominant under coniferous forest, the second under deciduous or broad-leaved forest, and the third under steppe and prairie. This third method, when modified to include the incorporation of plant remains throughout an appreciable depth of soil, is that used by farmers when they plough in farmyard manure or green crops, or when they put the land down to temporary leys.

The type of soil formed in a given region depends not only on the climate and the vegetation, but also on the topography of the land, the goodness of drainage and the parent material from which the soil is being formed. The effect of topography is mainly through the direction in which the products of weathering move on the one hand and the goodness of drainage on the other. The effect of drainage is both through the rate at which products of weathering are removed or accumulate within the root zone, and also on the oxygen content of the soil air. For poor drainage typically has the consequence that

no oxygen can reach the lower layers of the soil, hence reducing conditions set in. The parent material affects both the vegetation and the products of weathering and of accumulation, for the various minerals composing it have different rates of weathering and release different proportions of plant nutrients and of decomposition products during the process of weathering.

The effects of these soil-forming agents will be illustrated by examples in the following chapters. A detailed description of the various soil types that have been recognised, and of the various schemes of soil classification that have been suggested will not be given here, as several books devoted to these subjects are available.[1] It has become customary to classify soils into three divisions: the zonal, intrazonal and azonal soils. Azonal soils have not been under the influence of soil-forming processes long enough for their parent material to be appreciably affected, and alluvial soils in the temperate regions are typical examples of this group. In the zonal and intrazonal soils the parent material in the superficial layers has been appreciably affected by the soil-forming processes, the zonal soils being those formed on well-drained sites. Thus soils with impeded or transverse drainage, and swamp, marsh and salt soils, are examples of intrazonal soils. Soils in which the parent material has a pronounced but temporary effect on the soil-forming processes are also usually regarded as intrazonal, but this is normally restricted to soils forming on parent material rich in calcium carbonate. Thus, soils developing on chalk and limestone are considered intrazonal as long as any influence that the chalk or limestone may have had on the process of soil formation persists.

It is, however, very difficult to give any precise definition of the terms zonal, intrazonal and azonal. The concept of zonal soils was first introduced by the Russian pedologists when they were developing the theory that soil type was fundamentally determined by the climate, that is, that each climatic zone had its characteristic zonal soil type. But the concept has become progressively less precise as the deficiencies of this simple theory have been recognised.

[1] See, for example, G. W. Robinson, *Soils; Their Origin, Constitution and Classification*, 3rd ed., London, 1949; A. A. J. de Sigmond, *Principles of Soil Science*, London, 1938; J. S. Joffe, *Pedology*, 2nd ed., New Brunswick, 1949; S. A. Wilde, *Forest Soils and Forest Growth*, Waltham, Mass., 1946. For a recent symposium on Soil Classification, see *Soil Sci.*, 1949, **67**, 77.

CHAPTER XXX

SOIL FORMATION ON WELL-DRAINED SITES

The Humus of the Forest Floor

Two characteristic types of humus can be formed on the forest floor of well-drained sites known as mor and mull respectively. Mor formation typically occurs when the leaf litter and the humus produced by its decomposition lie on the surface of the mineral soil, and mull formation when the litter is rapidly mixed with the mineral soil particles, so the decomposition occurs in the superficial layers of the soil instead of on its surface. P. E. Müller, a famous Danish forester, first recognised and named these two types of humus in 1878,[1] and although foresters were at first slow to see the value of this separation, it is now recognised as being of considerable importance for forestry practice in the temperate regions. But well developed typical mor and mull are really two extreme types of humus, although they are developed over wide areas: there are also a whole range of transitional types formed where there is some mixing of plant debris with the mineral matter of the soil, but where this mixing goes on at too slow a rate to give a typical mull. Further, there are considerable variations in the types of humus present in typical mor and mull, as defined above.[2] There is much that is not yet understood about mor and mull formation, and in particular it is not always possible to predict if a change in forestry practice will cause an appreciable effect on the type of humus being formed,[3] though this is not necessarily of great practical importance for many trees will grow equally well on a soil whether the humus is present as a mor or a mull.

Mor formation typically occurs under coniferous forests and heaths growing on very well-drained soils low in available calcium, and which are in consequence very acid; but it can also occur on rather badly-drained soils, under deciduous forest, and on only mildly acid soils. The organic layer is often matted, lies like a carpet on the mineral soil, and has a low ash content. It shows a gradual transition from the undecomposed litter on the surface through layers in which it is decomposing but in which some of the original leaf structure remains

[1] *Tidsskr. f. Skovbrug*, 1878, **3**, 1; 1884, **7**, 1; *Studien über die natürlichen Humusformen*, 1887, Berlin; *Ann. Sci. Agron.*, 1889, **1**, 85.

[2] See, for example, H. Hesselman, *Medd. Skogsförsöksanst.*, 1926, **22**, 169; 1927, **23**, 337; L. G. Romell and S. O. Heiberg, *Ecology*, 1931, **12**, 567; S. O. Heiberg and R. F. Chandler, *Soil Sci.*, 1941, **52**, 87.

[3] For a discussion of this, see L. G. Romell, *Cornell Agric. Expt. Sta., Mem.* 170, 1935.

recognisable—Hesselman's F-layer[1]—to a layer of dark, structureless humus below, Hesselman's H-layer.

Mull formation typically occurs under deciduous or mixed forests growing on moderately well-drained soils reasonably supplied with calcium, but it can occur under coniferous forests, particularly if they contain cedars or certain species of spruce whose litter has a high calcium content.[2] Thus, mulls are usually less acid than mors, but are not necessarily so. Their acidity does not fall below *p*H 4·5 and may be as high as *p*H 8, whilst that of a mor may fall to *p*H 3, and be as high as 6·5. The organic layer is crumbly and most of it is mixed with a high proportion of soil particles, so it may only contain as little as 10 per cent of organic matter, and there is a gradual transition from the surface mull to the mineral soil. The mull layer is what the gardener calls leaf or vegetable mould, and if it were not that the sound of the word would lead to confusion with certain types of fungi, this type of humus should have been called mould and not mull in English. Mull soils typically contain many earthworms and often harbour many moles, voles and mice, which burrow extensively under the surface, keeping the surface layers very loose and helping in the mixing of the litter with the soil.

Unfortunately, the number of firmly established facts about the process of mull and mor formation are scanty, so that even the cause of their formation is not agreed. It is probable, however, that the principal agents directly controlling which type of humus is formed are the predominant groups of soil animals present in it. Mull appears to be the characteristic humus formed when earthworms are the predominant group, transitional types of humus when the dominant soil fauna are millepedes, woodlice or larvae of the larger insects or termites, and typical mor when they are mites and springtails. This transitional type of humus in Europe, where termites are of no importance, was called "insect mull" by Müller, and is a mor, in that there is a fairly sharp boundary between the humus and the soil, but the F-layer is weakly developed and the H-layer is usually crumbly, shows little trace of the original structure of the dead litter, and is mainly composed of the excreta of the soil fauna by which it has been produced. Thus, mull types of humus seem to be characteristic of decomposed organic matter that has passed at least once through the alimentary canal of one of the larger soil animals, whilst typical mor humus has not. There is no reason to believe that the decomposed organic matter suffers a different type of change in passing through a mite than a

[1] "F" is short for Förmultningskikt, or fermentation layer, and "H" for Humusämneskikt, or humus layer.

[2] See, for example, M. J. Plice, *Cornell Agric. Expt. Sta., Mem.* 166, 1934; R. F. Chandler, ibid., *Mem.* 228, 1939.

millepede or insect larva: it is in the proportion of the organic matter which has passed through that the typical mor differs from the typical mull.[1]

On this concept, the factors controlling mull or mor formation are effective through their control of the animal population. Thus, in north-west Europe, earthworms only occur in soils that are adequately supplied with available calcium, reasonably deep and reasonably well-drained. Earthworms need an adequate depth of soil for hibernation and aestivation, and they also need a soil with a reasonable moisture holding capacity, for they do not flourish in very dry soils such as coarse sands and gravels. Thus, heath soils and thin soils over rock typically have mor humus developing on them. The conditions under which millepedes, woodlice and the larvae of the larger insects become dominant in temperate regions are not yet known, though W. Kubiena,[2] working in some mountain limestone soils of Austria, found that this occurred after a certain depth of soil had accumulated, but before it was deep enough for earthworms to flourish; so it is possible that they only form the dominant soil fauna when all circumstances except depth of soil are suited to earthworms.

On this concept one of the roles of soil micro-organisms in the production of humus is to prepare the leaf litter for use by the larger soil animals. In typical mor, the fungi are often considered to be the predominant group of micro-organism, and they convert much of the leaf litter into their own protoplasm which is a form that the mites in particular can digest. However, although fungal mycelia and fungal-eating mites are very common in many such mors, no quantitative proof has yet been given that the fungi are, in fact, the most important group of micro-organisms in decomposing the leaf litter. The conditions in a mor are, however, usually too acid for many groups of bacteria to develop. Thus, nitrifying bacteria are typically either absent or present in very small numbers, so mor soils do not contain detectable amounts of nitrates in the field, though they may yield some nitrate when incubated in the laboratory. However, mor soils are also characterised by only containing very small amounts of ammonium nitrogen, probably because of the intense demands of the micro-organisms for available nitrogen, as the litter has usually a low nitrogen content. Further, the roots of trees growing on mor are usually concentrated in the humus layer and covered with mycorrhiza, so the plants are also strongly competing for the available nitrogen there.

No complete fractionation of mor humus has yet been made, but its

[1] See, for example, T. H. Eaton and R. F. Chandler, *Cornell Agric. Expt. Sta., Mem.* 247, 1942.

[2] *Bodenk. PflErnahr.*, 1942, **29**, 108; 1944, **35**, 22; *Entwicklungslehre des Bodens*, Vienna, 1948.

fulvic acid fraction appears to contain a relatively high proportion of readily dispersible nitrogen compounds. The humus in the mor rapidly releases ammonium nitrogen when the trees have been felled or sufficiently heavily lopped to kill the mycorrhizal fungi, or when it is brought into the laboratory. This ammonia is probably derived from the decomposition of the fungal mycelia in the humus layer but this has not yet been proved.

Bacteria are probably the most important microbial agents of decomposition in mull, and aerobic cellulose decomposers are usually abundant. The soils always nitrify well and differ from mors in having a higher content of ammonium and nitrate nitrogen in the natural state, but in not forming these compounds so quickly when samples are incubated in the laboratory. On the other hand, the roots of the trees and the undergrowth are not concentrated in the mull layer, but extend through a considerable depth of soil, and the roots usually only carry few mycorrhiza. The humus has a lower proportion of the fulvic acid fraction, is less easily mobile and more saturated with calcium than that in a mor, and its humic acid fraction has probably a higher nitrogen content and a higher base exchange capacity.

The fact that the organic matter in the bulk of the mull layer is structureless does not mean that decomposition takes place more rapidly in the mull than in the mor, for the opposite is probably more often true. It is simply a reflection of the fact that earthworms not only mix the leaf litter with the soil, but so macerate it in their gut that all trace of its original structure has been lost in the excrement.

An example of the effect of the absence of earthworms and of extreme shallow rooting habit in encouraging mor formation is well illustrated on the Rothamsted Grass Plots, which are part of an old meadow cut annually for hay. Where the soil has been rendered very acid by repeated high dressings of sulphate of ammonia, a layer of dead grass litter has been converted into a definite mor. There are no earthworms in the soil, and the grasses are very shallow rooting and suffer quickly in droughts, but if the litter is mixed with the soil in the laboratory, decomposition of the mor rapidly takes place.

Well-drained Soils under Mor: the Podsol

The soil developed under well-drained mor is the podsol, which is characterised by having a band of light-coloured soil fairly sharply separated from a darker layer of soil above and below it. It is this band of light soil which has given the podsol its name, for the word signifies in Russian ash-coloured soil. The podsol profile can be divided into several clearly defined layers or horizons. The upper is the mor

and is commonly called the A_0 horizon, and is brown to black in colour. Below this comes the top layer of mineral soil, which is also dark in colour, the A_1 horizon, but on many sites this is not developed, and below the A_1 comes the light-coloured bleached layer, or A_2. The next layer, called the B, is dark coloured and usually lightens gradually with depth until it becomes indistinguishable from the parent material or the C horizon. Since the surface humus is a mor, the division between the A_0 and A_1, or A_2 if there is no A_1, is sharp, and the divisions between the A_1 and A_2 and between the A_2 and B are sharp, but the divisions in the B horizon itself, and between the B and C horizons are gradual.

The relative thickness of these layers is very variable, but the cause of the variability cannot always be given. The A_0 can be very thin and the A_1 well developed, as on heaths and some forests with suitable undergrowth, or the A_0 can be well developed and the A_1 thin or lacking. Thus, in well-developed podsols under coniferous forest on sandy soils there is no A_1 horizon—the mor lies directly on the A_2—and this is probably the profile originally defined as the podsol by the Russians. Similarly, the thickness of the A_2 and of the B varies very considerably, often in quite small areas; and in particular the boundary between the A_2 and the top of the B is often extremely irregular, varying by over 6 inches in very short distances. The total depth of the profile, that is, from the top of the A_0 to the bottom of the B, can vary from a few centimetres to over a metre.

This profile is most clearly developed on coarse, sandy soils rich in quartz grains, for these resistant grains give a large visible surface that can suffer bleaching. As the soil becomes heavier, the separation between the horizons becomes less distinct, until the B may only appear as darker coloured spots or streaks in a uniform bed of parent material. In northern Europe, podsols are extensively developed over the great area of sands left behind by the ice sheets in the glacial period.

The chemical characteristics of the podsol profile are:

1. The *p*H is usually lowest in the A_0 horizon and increases down the profile, though in some profiles the A_1 may be the most acid.

2. The A_0 and A_1 horizons have a high base exchange capacity, but are very unsaturated. The percentage saturation usually increases down the profile, but because of the low exchange capacity of the A_2 and below, the actual number of milli-equivalents of base, chiefly calcium, may be highest in the A_0 or A_1.

3. The A_2 horizon is subjected to intense weathering, as can be seen from an examination of the fine sand grains. All those of easily weatherable minerals have either disappeared or are obviously being heavily attacked. Thus, minerals very resistant to weathering, such as quartz,

tend to accumulate in it. There is no evidence that any secondary minerals are formed in this layer.

4. The B horizon is enriched with material that has been washed out of the A horizons, and it is therefore often called an illuvial horizon in contrast to the A's which are known as eluvial. It is enriched with organic matter, clay, and iron and aluminium hydroxides, and often the zone of their maximum accumulation occurs at its top. But, whilst this is probably always true for the organic matter, the maximum for the clay may be in the bottom part of the A_2, and for the iron and aluminium hydroxides below the top of the B. It is very common in Great Britain to find a thin hard pan, often only a few millimetres thick, on top of the B horizon, which is sometimes referred to as the "walnut shell layer" and which is the zone of maximum iron, and possibly of organic matter, accumulation. Table 123[1] illustrates many of these points for a podsol developed under forest in Morayshire, Scotland.

Much of the iron and aluminium deposited in the B horizon is present as hydroxides or hydrated oxides, as can be shown both by the solubility of the iron and aluminium compounds in such solvents as Tamm's acid oxalate and by the power of the soil in the B horizon to absorb acidic dyes. Fig. 46[2] shows the amount of iron and aluminium extracted by Tamm's acid oxalate from a typical podsol of the type being discussed, called an iron podsol in the figure (the iron-humus podsol will be discussed on p. 537): it is greatest at the top of the B horizon and decreases downwards until it falls to a low level in the C. Acidic dye absorption, which can probably only take place on the iron and aluminium hydrated oxides and hydroxides in this layer, follows the acid extract curves very closely.[3]

It is possible, but not yet proven, that some of the aluminium entering the B horizon reacts with soluble silica there to give kaolinitic, or possibly illitic, clays. The B horizon certainly contains these clays,[4] and it is very probable they are being formed there, but this has not yet been proved. On the other hand, D. M. C. MacEwan[5] has shown that in the B horizon of some Scottish podsols, biotites appear to be converted into hydrobiotites and vermiculites and thence into illites, a conversion that does not necessitate the complete disruption of the original biotite lattice.

Much still remains obscure about the chemistry of the podsolisation process, and the two problems that are still unsolved concern the agent that mobilises the iron and aluminium in the A layers and carries them

[1] A. Muir, *Forestry*, 1934, **8**, 25.
[2] Taken from K. Lundblad, *Soil Sci.*, 1934, **37**, 137.
[3] K. Lundblad, *Soil Sci.*, 1936, **41**, 383.
[4] L. T. Alexander, S. B. Hendricks and R. A. Nelson, *Soil Sci.*, 1939, **48**, 273.
[5] *Verre et Silic. Indust.*, 1948, **13**, 41.

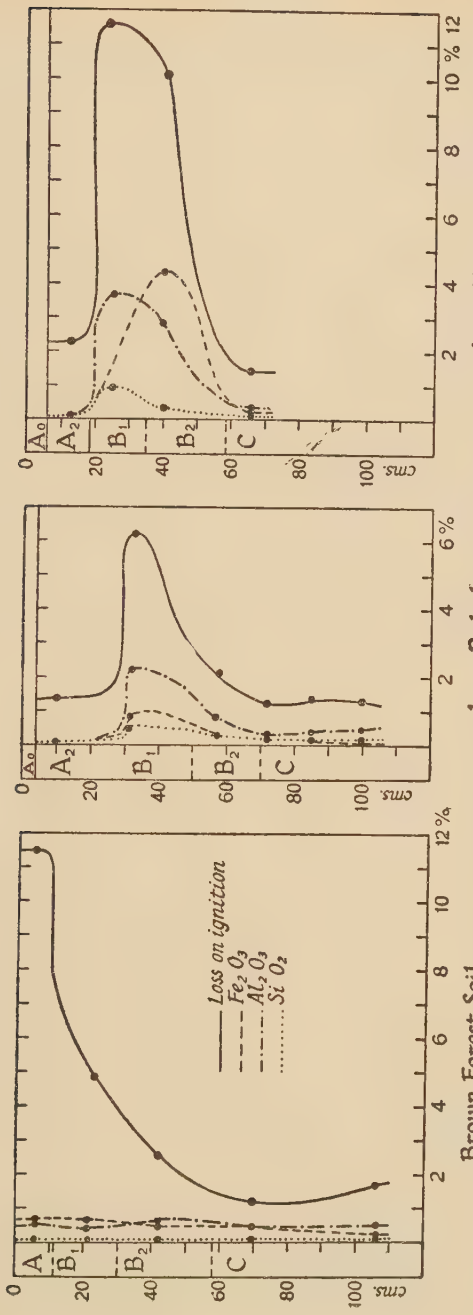


FIG. 46. Loss on ignition and amounts of silica and sesquioxides extracted by the acid-oxalate method in a Swedish brown forest soil, iron podsol and iron-humus podsol.

TABLE 123

Analysis of the Various Horizons of a Podsol Profile in Teindland State Forest, Morayshire

(A) Ultimate analysis as percentage of ignited fine earth (< 2 mm.)

Horizon	A_1 5–7 cm.	A_2 7–14 cm.	B_1 14–16 cm.	B_2 16–26 cm.	B_3 26–50 cm.	C 60–70 cm.
SiO_2	89·43	91·05	82·49	78·86	76·40	83·12
TiO_2	0·14	0·12	0·24	0·21	0·21	0·11
Al_2O_3	6·11	5·81	10·10	10·30	11·08	8·56
Fe_2O_3	0·89	0·55	2·71	3·59	3·32	2·19
CaO	0·63	0·45	0·52	0·68	0·94	0·59
MgO	0·30	0·54	0·40	0·22	0·71	0·46
Undetermined residue[1]	2·50	1·78	3·54	6·14	7·34	4·87
Total	100·00	100·00	100·00	100·00	100·00	100·00
Loss on ignition	38·73	1·77	7·87	5·66	3·92	1·63
Moisture (105°)	12·02	0·65	5·41	4·72	4·12	1·46
Clay content	—	4·75	12·32	10·12	9·25	4·58

(B) Analysis of clay fraction: as percentage of ignited clay

Horizon	A_2 7–14 cm.	B_1 14–16 cm.	B_2 16–26 cm.	B_3 30–40 cm.	C 60–70 cm.
SiO_2	59·02	46·28	31·73	33·80	35·20
TiO_2	3·59	1·19	1·82	1·50	1·00
Al_2O_3	24·20	29·92	38·36	31·62	24·56
Fe_2O_3	4·18	14·36	20·42	21·71	18·80
SiO_2/R_2O_3	3·71	2·00	0·95	1·26	1·63
SiO_2/Al_2O_3	4·12	2·61	1·03	1·80	1·92
Al_2O_3/Fe_2O_3	9·09	3·28	4·01	2·30	2·59

(C) Absorbed bases per 100 gm. of oven-dry soil, and pH value

Horizon	A_0	A_1	A_2	B_1	B_2	B_3	C
m.-eq. Calcium	7·0	3·0	0·8	1·1	0·5	0·8	0·8
m.-eq. Magnesium	n.d.	2·6	1·0	1·0	0·9	0·8	0·8
m.-eq. Hydrogen	n.d.	46·2	1·6	23·1	12·2	6·9	2·9
*p*H	3·7	3·9	4·3	4·5	4·5	4·8	5·1

down into the B, and the agent that causes the iron and aluminium to be precipitated in the B.

It has long been suspected that there was a connection between the movement of organic matter from the A_0 and A_1 horizons into the B and the solution and transport of the iron and aluminium. The crux of

[1] Probably chiefly K_2O and Na_2O.

this problem hinges on the fraction of the organic matter responsible. There are two different processes, both of which are possible on our present knowledge. Finely dispersed acid humus particles can mobilise the hydrated ferric oxide formed during the weathering process, and carry it down into the subsoil. This process is the one that has been most commonly assumed to be operative, and B. C. Deb[1] has recently shown that under conditions which may very likely prevail in the surface layers of a podsol, this finely dispersed humus can carry down from three to ten times its weight of iron oxide.

The second possible process is that polybasic carboxylic acids are the principal agents for carrying down the iron oxide. It is known that acids such as oxalic, citric and tartaric are all capable, even in weak solutions, of bringing into solution iron and aluminium in the form of co-ordination compounds,[2] that the free acid is not necessary but only the free anion,[3] and that these acids are typical metabolic by-products of the fungi in the mor layer. But their presence has only been assumed and not actually demonstrated in the downward moving water.[4] It is just possible that the mechanism by which finely dispersed acid humic particles mobilise the iron is through the iron forming co-ordination compounds with its carboxylic acids, in which case the two processes described would both operate through the same mechanism.

The second problem concerns the cause of the deposition of the iron and aluminium in the B horizons. The problem is complicated by the probable fact, to be discussed on p. 522, that only a part, and perhaps a small part, of the iron and aluminium removed from the A layers is deposited in the B, although the current theories on the cause of this deposition all assume that it is complete. The principal theories at present advocated assume that the primary cause of the precipitation is the increased *p*H in the B horizon. Colloidal particles of iron and aluminium, probably as hydroxides, are assumed to acquire a negative charge under the highly acid conditions in the A layers by becoming coated with humic or silicic acids. This charge is sufficiently great for the colloidal particles to disperse in the downward-moving water, but it falls rapidly as the *p*H increases at the base of the A_2 and the top of the B horizons so that the particles cease to be dispersed in the water and precipitate out. This theory naturally assumes that the iron and aluminium are not in co-ordination compounds with simple organic

[1] *J. Soil Sci.*, 1949, **1**, 112.

[2] H. T. Jones and J. S. Willcox, *J. Soc. Chem. Indust.*, 1929, **48**, 304 T.

[3] For the kind of experimental justification available for theories of this type, see P. H. Gallagher, *Proc. Roy. Irish Acad.*, 1942, **48** B, 213. W. J. Dyer and W. D. McFarlane (*Canad. J. Res.*, 1938, **16** B, 91) considered they had evidence that some of the iron in the B layer was in co-ordination compounds of this type.

[4] P. H. Gallagher and T. Walsh, *Proc. Roy. Irish Acad.*, 1943, **49** B, 1.

acids, for these compounds would remain soluble in solutions considerably less acid than are present in the top of the B.

An alternative theory can probably be based on a mechanism similar to that postulated by H. Jenny and G. D. Smith, to be discussed on p. 540, for the formation of clay pans. Silicic and humic acids could be deposited on the mineral particles on the B horizon during summer droughts, which would give them a negatively charged surface on which, later in the year, the iron and aluminium co-ordination compounds in the downward-moving water would be precipitated as the organic acids mobilising them became attacked by the micro-organisms in this layer. This hydroxide layer would then cause silicic or humic acid, moving in the percolating water, to precipitate on it to neutralise its positive charge. Such a theory may probably come fairly close in many ways to S. Mattson's theory of isoelectric weathering,[1] for he postulates that the cause of material being precipitated in the B horizon is that it is isoelectric at the *p*H prevailing there. The precipitates are pictured as being built continuously by their removing the requisite proportions of aluminium, iron, silicic and humic acids from the compounds dissolved in the percolating water to give new precipitates that are isoelectric, that is, carry no net electric charge, in the percolating solution.

However, before much further headway can be made in the theory of podsolisation, more factual information is required. Thus, more knowledge is required of the forms of organic matter that actually move down through the A_2 horizon. The newer methods of humus analysis should be able to give a more accurate description of the organic materials that move from the A_0 into the top of B horizon,[2] although they would miss any ephemeral components such as oxalic or tartaric acids, supposing them to be present in low concentrations in the downward-percolating water. Again, not enough is known of the fate of the products of weathering mobilised in the A layers, for not all of them are precipitated in the B. Thus, analyses of the water from springs and rivers show that some of the silicon is washed out of the profile altogether, and this appears to be true for the iron and aluminium also. Thus, A. A. Rode[3] has calculated the loss of constituents from a podsol profile in Russia by assuming that the quartz in the original deposit was uniformly distributed throughout the profile and that none of it had weathered. These results are given in Table 124, which shows that the loss of iron and aluminium together from the whole profile is comparable

[1] *Soil Sci.*, 1932, **34**, 209, and a series of papers in *LantbrHögsk. Ann.*, beginning 1934, but particularly 1935, **2**, 115; 1937, **4**, 1; 1942, **10**, 241.

[2] For some recent publications, see P. H. Gallagher, *Proc. Roy. Irish Acad.*, 1942, **48** B, 213; I. V. Tiurin, *Pedology*, 1944, No. 10, 441.

[3] *The Soils of the U.S.S.R.*, Vol. I, p. 181, ed. L. I. Prasolov, Moscow, 1939.

with the loss of silicon, and though the losses are greatest in the A_2 horizon, yet they are appreciable in the B.

TABLE 124

Weight of Soil Constituents Lost during Podsolisation

In tons per acre

Horizon	Si	Al	Fe	Mg	K	Ca	Na
A_1, 0–9 cm.	74	44	25	7	10	4	4
A_2, 9–26 cm.	138	88	48	14	19	9	7
A_2B, 26–35 cm.	43	30	16	5	6	4	3
B_2, 35–50 cm.	18	11	4	2	1	4	2
B, 50–63 cm.	8	4	2	1	—	—	1
Total, 0–63 cm.	281	177	95	29	36	21	17
Average annual loss, assuming soil 10,000 years old, in pounds per acre							
A_1 and A_2	48	30	16	5	7	3	2
Total	63	40	21	7	8	5	4
Tamm's estimate for young Swedish Podsols							
A	25	10	7	3	4	2	2

O. Tamm[1] has also found that there is a net loss of iron and aluminium from the B horizon, and R. P. Matelski and L. M. Turk[2] have shown from an optical examination of the minerals in the fine sand fraction of a Michigan podsol that weathering proceeds actively in this zone. In fact, they claim that horneblende weathers more easily in the B than in the A horizons.

Rode also calculated the average rate of loss of constituents from the Russian profile, assuming it has taken 10,000 years to develop. The figures so found, which are also given in Table 124, imply a higher rate of weathering than for Europe as a whole, as deduced from the analyses of river waters given on p. 502, but unfortunately Rode does not say what were the parent mineral particles in the deposit. His results are also rather higher than some previously obtained by O. Tamm,[3] also given in Table 124, and obtained by a similar method, for the rate of removal of constituents from the A horizons of some young Swedish podsols developed on river sand.

The time taken for a podsol to develop its typical profile depends on many conditions, but on sandy soils under coniferous forest between 1,000 to 1,500 years is adequate,[4] though Tamm also finds that an A_2 horizon 1 cm. thick can be formed in 100 years, and A. Muir[5] gives

[1] *Medd. Skogsförsöksanst.*, 1932, **26**, 163.
[2] *Soil Sci.*, 1947, **64**, 469.
[3] *Medd. Skogsförsöksanst.*, 1920, **17**, 49.
[4] O. Tamm, *Medd. Skogsförsöksanst.*, 1920, **17**, 49; R. F. Chandler, *Proc. Soil Sci. Soc. Amer.*, 1943, **7**, 454 (for an example from Alaska).
[5] *Forestry*, 1934, **8**, 25.

an example of an A_2 horizon 0·5 cm. thick being formed in twenty years in Kincardineshire.

The podsol profile can be altered very considerably if the drainage becomes impeded, but these alterations will be discussed in the next chapter, in which the general problem of the effect of impeded drainage on soil formation will be discussed.

Well-drained Soils under Mull: the Brown Earths

The typical brown earth differs from the true podsol in three respects: it is found on loams and clays rather than on sands, hence it has a lower air content during wet weather and may even be subject to slight reducing conditions during part of the year; it has a higher content of exchangeable calcium though it is typically acid; and there are no sharp horizons between the different layers in the profile.

The typical forest soil profile under mull begins with a layer of undecomposed litter, then comes a fairly deep layer of crumbly soil whose organic matter content decreases slowly downwards until it gradually grades into the unweathered subsoil. The name brown earth or brown forest soil describes the colour of this layer.

The chemical analysis of the profile shows the following characteristics. The *p*H and the proportion of exchangeable calcium usually increases gradually down the profile. The organic matter content decreases gradually down the profile, and there is no zone in the subsoil of organic matter accumulation. The profile shows the typical effects of weathering, namely, the mineral particles are attacked and the bases and silicon tend to wash out and the aluminium and iron to remain behind, though the intensity of weathering is much less severe than in the A horizon of podsols. There is little free iron and aluminium hydroxides in the profile, as shown by the small amount of these dissolved out by Tamm's acid oxalate, as can be seen in Fig. 46 on p. 519.

The outstanding product of accumulation is kaolinitic and illitic clay, which is formed all through the profile. On mature soils there is often a layer enriched in clay[1] due either to it being a layer of active clay synthesis or to it being a layer of accumulation of clay synthesised nearer the surface and washed down and held either mechanically in the fine pores or else by coagulation and drying on other particles.[2] This process can proceed so far that the layer has become almost

[1] Soils with this layer of enrichment are known as grey-brown podsolic in America, for descriptions of which see M. Baldwin, *Proc. 1st Int. Congr. Soil Sci.*, Washington, 1927, **5**, 276; M. G. Cline, *Soil Sci.*, 1949, **68**, 259.

[2] H. Pallmann, E. Frei and H. Hamdi, *Ber. Schweiz. Bot. Ges.*, 1943, **53** A, 175; *Kolloid.-Ztschr.*, 1943, **103**, 111.

impermeable, giving the planosol soil which is characteristic of very level topography under these conditions in America. The chemical analysis of the profile also often shows a zone of relative enrichment with aluminium, that corresponds with the zone of clay enrichment. This may simply be a reflection of the fact that kaolinite clay has a high aluminium content compared with most rock minerals, but no suitable field results seem to be available to test if this is the whole cause of the apparent aluminium enrichment in the B horizon.

Natural brown earths under forest are rare in England and much of Europe because these soils have been cultivated for many centuries, as they are naturally more suitable than the podsols for agricultural crops. Brown earths also occur on hill slopes, but these will be discussed in the next chapter, as they form an example of the effect of topography on soil formation.

It must again be emphasised that there is a whole range of soils between the true podsol and the typical brown earth, for there are all transitions between mull and mor on the one hand and between very free draining sands and slow draining clays on the other. Hence there are soils showing all gradations in such properties as the amount of dispersed humic, iron and aluminium compounds that move into the subsoil and the quantity of clay that is synthesised. Soils in this transitional range are usually known as podsolic—a type that is extensively developed in America.

The Grassland Soils: the Prairie Soils and Chernozems

Grasses differ from forests in that they translocate much of the organic matter they synthesise into the soil as root system. As already mentioned on p. 431, grasses can add over a ton of dry matter to the soil per year as roots, and natural grassland soils may contain over 5 tons per acre of roots below ground compared with only 1 to 2 tons of above-ground material. Thus, J. E. Weaver, V. H. Hougen and M. D. Weldon[1] give the following weights of organic matter and roots in a Nebraska prairie, in tons per acre:

Depth	0–6 in.	6–12 in.	1–2 ft.	2–3 ft.	3–4 ft.
Weight of roots	2·6	0·72	0·63	0·30	0·04
Weight of organic matter	31·0[2]	26·0	26·0	8·1	4·0
Weight of roots as per cent of organic matter	8·5	2·8	2·3	3·6	1·1

[1] *Bot. Gaz.*, 1935, **96**, 389. J. E. Weaver and E. Zink (*Ecol.*, 1946, **27**, 115) give further figures for the annual rate of production of roots by three prairie grasses at different depths in the soil.

[2] This figure includes the rhizomes of grasses which occurred in the top 6 inches.

This difference between grassland and forest is also illustrated in Plate XXVII, which shows the profiles, with the distribution of organic carbon down the profile, of a prairie and a deciduous forest soil both on the same parent material, and both from Iowa. Although the prairie soil only contains 50 per cent more organic matter than the forest, yet it is distributed through a considerably greater depth of soil.

The grass roots themselves are extensive and fine, hence, as shown in Table 98, on p. 432, they may have a very great length in the soil and many of the finer roots will decompose quickly. These soils also typically have a large population of earthworms, and also of rodents, which may make extensive burrows and nests in the soil well below the soil surface. Hence, little litter accumulates on the surface, most of it being worked into the top layers of the soil, as in the brown forest soils.

Grassland soils occur naturally in climates that are too dry for forests, although they can also be found on limestones and chalks in the more humid regions. Thus, as both E. M. Crowther and H. Erhart[1] have pointed out, they are characteristic of regions subject to summer droughts sufficiently severe for the available water in the root zone of the soil to be exhausted before the drought breaks. Grasses can withstand these conditions far better than deciduous forest, hence their dominance.

Grassland soils can be roughly divided into three types: the prairie, the chernozem and the chestnut. The typical prairie soils are formed where the summer rainfall is only just too little for deciduous forest, but where there is sufficient rainfall during the rest of the year for considerable leaching to take place. The chernozem soils are developed under rather more arid conditions where little water leaches out of the root zone, and the chestnut under still more arid conditions when the rain-water rarely if ever leaches through the profile. Thus, the prairie soil typically has a weakly leached profile so that the soil may be slightly acid all the way down, the chernozem has a weakly leached surface soil, which may be slightly acid, but has a zone of precipitation of calcium carbonate at the base of a deep root zone, whilst the chestnut soil has a neutral surface soil and its zone of calcium carbonate accumulation comes nearer the surface as the depth to which the rain normally penetrates becomes shallower. The leaching in the chestnut soil is so restricted that at the base of the layer of calcium carbonate accumulation comes a layer of calcium sulphate accumulation. These grassland soils have a very characteristic soil structure. The crumbs are small and friable, sometimes breaking down almost to a dust in the surface and become larger, angular and stronger in the deeper layers of the profile, and have considerable water stability. Plate XXX

[1] *Traité de Pédologie*, Strasbourg, 1935.

gives an illustration, in semi-diagrammatic form, of this structure in a well-developed chernozem, and Plate XXII gives a photograph of actual soil crumbs in a chernozem soil adhering to grass roots.

The prairie soils are similar in many respects to the brown forest soils. The surface layers are often somewhat acid, due to leaching, there is a washing down of organic matter and clay, and clay formation takes place in the profile. But there is probably a greater annual circulation, and hence a greater movement, of silica in prairie than in forest soils, for grasses have a much higher silicon content than tree leaves. As in the brown forest soils, a pronounced clay pan may be formed both by clay being actively formed in this layer and also by clay formed higher up the profile being washed down into it. Otherwise weathering is not very severe. Thus, J. F. Haseman and C. E. Marshall[1] showed that in the Grundy silt loam, a typical prairie soil developed on loess in Missouri, the sand grains larger than 0·046 mm. have barely been weathered at all, the silt particles between 0·025 and 0·002 mm. have been washed down from the top foot into the third and fourth foot, the easily weatherable minerals in the top 2 feet have been attacked, and clay accumulation has taken place in the layer $1\frac{1}{2}$ to $4\frac{1}{2}$ feet below the surface. The clay may be mainly illite or it may be an illite-beidellite mixture with the illite more in the larger and the beidellite or montmorillonite more in the finest fraction.[2]

These soils are well developed in the corn belt of the Middle Western States of America. They are fertile, or can be made so by adding fertilisers, and the rainfall is adequate for excellent crops of maize and soybeans if the land is properly farmed. It is to this soil type that the Western European farmer tries to convert his soil by using leys and farmyard manure.

The chernozems, or black earths, to give the English translation of the Russian word, are so called because of their black colour, which may extend down to a depth of 3 to 6 feet, though the colour lightens with depth. The fundamental climatic characteristic of these soils is that there should be sufficient rainfall for the natural grasses to make good top and root growth, but not sufficient to allow any appreciable leaching. Thus, very little of the rain percolating into the soil ever reaches the ground-water or the rivers. As the amount of rain-water penetrating into the ground-water increases, so the soil type goes over into the prairie, and as the deficiency of the rainfall increases, so the maximum depth to which the soil is wetted each year decreases, and it goes over to the chestnut. The true Russian chernozem occurs in a climate with hot summers and cold winters. In the winter the soil is

[1] *Missouri Agric. Expt. Sta., Res. Bull.* 387, 1945.
[2] See also W. E. Larson *et al.*, *Proc. Soil Sci. Soc. Amer.*, 1948, **12**, 420.

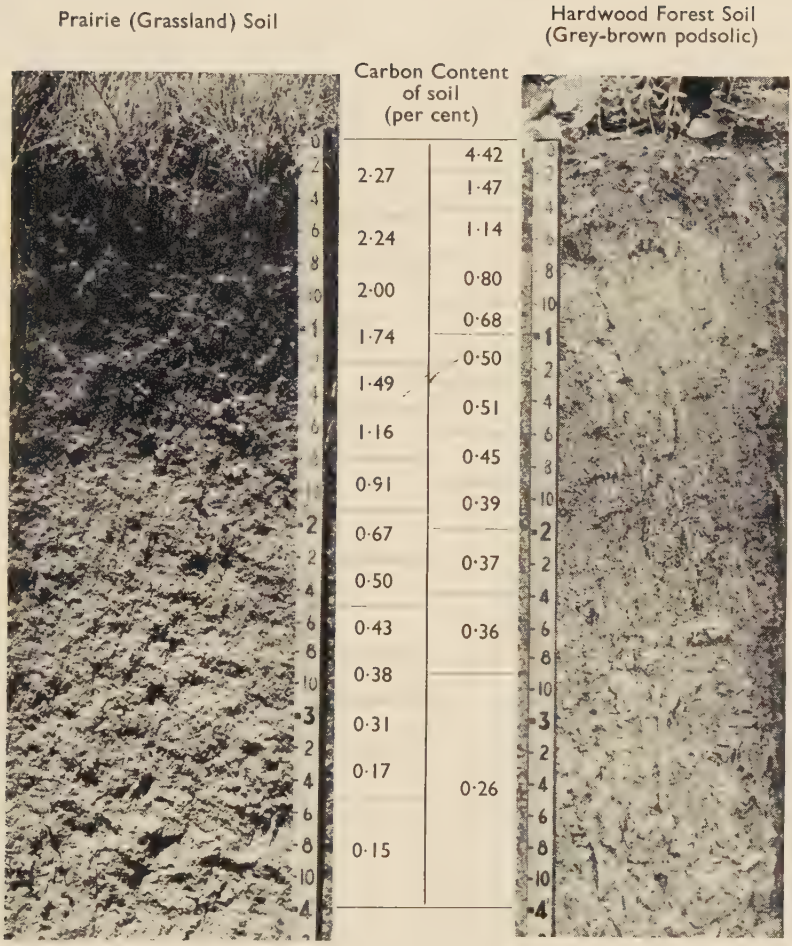
frozen for prolonged periods and much of the snow that falls runs off the frozen soil when it thaws in spring.

The soil of the chernozem is neutral or nearly neutral all down the profile, the exchange complex is typically saturated mainly with calcium, and soil organic matter is probably leached down the profile, though to what depth is not known. As shown on p. 525, the roots only account for 2 to 4 per cent of the organic matter in the deeper layers of the profile, so if no leaching takes place it would mean that it takes twenty-five to thirty years, on the average, for the organic matter in the roots to be oxidised away. The organic matter has a relatively high nitrogen content compared with that in most forest soils, its C/N ratio being about 10, and the type of humus is the grey humic acid mentioned on p. 257, which, according to Mattson (p. 268), is fully autoxidised and so has a high nitrogen content and a high base exchange capacity. Clay formation, predominantly of the beidellite type, occurs; but the rate of clay formation is much slower than in the prairie soils, and its chemical composition is nearly constant down the profile. There appears to be little translocation of silt or clay particles,[1] and clay pans, which are so characteristic of prairie soils, are less common in the chernozems.

However, under tropical conditions, where weathering can go on during the period the soil is wet because of the high temperature, but in regions where there is not enough rainfall for water to leach out of the root zone, so much beidellite or montmorillonite clay may be formed that the whole soil becomes an extremely heavy black clay carrying grass, or grass and scrub. In spite of the black colour the humus content may be fairly low, presumably again because of the high temperatures, and the only way water can move into the soil is through the large cracks that develop every dry season. They do not have a granular structure like a chernozem, but their subsoils have a very well pronounced columnar structure. These soils are typically formed from basic igneous rocks, probably because they contain a high proportion of minerals that weather easily and which release a high proportion of bases; they are found in many parts of Africa, and in the Dutch East Indies.

The chernozem is characterised also by having a zone of accumulation of calcium carbonate at a depth of about 6 feet. It is present as thin threads and films if the climate is only just arid enough for it to form, but as the climate becomes more arid, soft, white concretions appear. The three chernozem profiles, illustrated in Plate XXX, show this in semi-diagrammatic form. The deep chernozem is formed under the highest rainfall and the southern under the lowest, and the figure

[1] For a recent discussion of the characteristics of Russian chernozems, see L. I. Prasolov, *Dokuchaev Inst. Soils*, 1939, **1**, 225.



The profile and carbon content of a prairie and a hardwood forest soil on a silty loam in Iowa (Tama and Fayette Series respectively)
(*pp. 281, 526*)

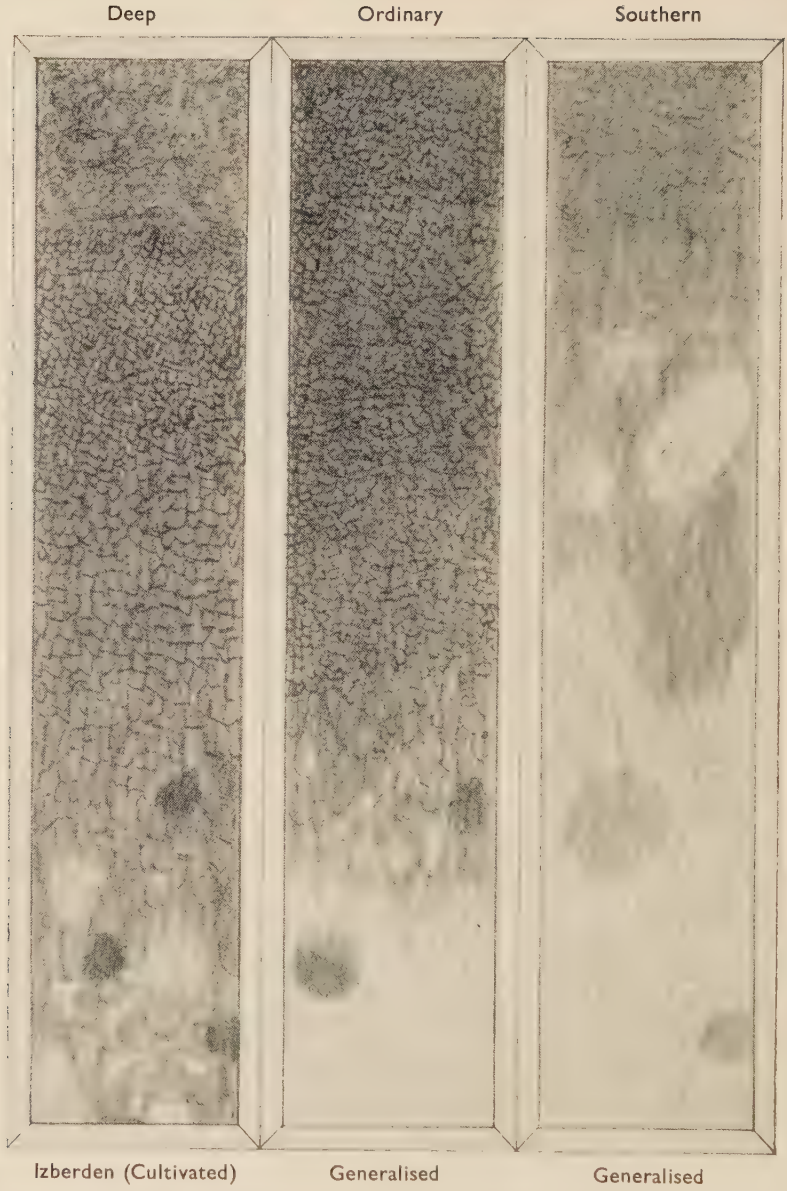
Nodular or pisolitic laterite with larger cavities, from the South Gate of Pimai, Nakorn Rachasima Province, North-eastern Siam, built in the ninth and tenth centuries A.D.

(*p. 508*)

Part of a quarried block of vesicular laterite from the city wall, built about 150 years ago, Muang Gao, Chantaburi Province, South-eastern Siam

(*p. 508*)

Plate XXX



Typical chernozem profiles

Deep Chernozem (Izberden): granular structure (disturbed by cultivation near surface), becoming pea-like and then nutty below; humus layer over 100 cm. in depth; carbonate as "pseudomycelium" below about 90 cm.

Ordinary (Medium) Chernozem: granular structure; humus layer 70–90 cm. deep; carbonate as efflorescence or pseudomycelium below about 70 cm.

Southern Chernozem: structure less well expressed, may be granular or crumb-like near surface; humus layer (often with chocolate-brown tint) 50–80 cm.; carbonate as a characteristic horizon of (soft concretions) "bieloglaska" or "white eyes" below about 70 cm.

(*p. 526*)

shows how the depth at which calcium carbonate is first deposited decreases as the climate becomes more arid. These profiles also show the characteristic burrows of steppe rodents filled in with dark-coloured surface soils. Below the layer of calcium carbonate accumulation in the more arid chernozems comes a zone in which calcium sulphate is precipitated as gypsum.

The chernozems are well developed on the calcareous loess soils that extend from Central Europe through Russia into Central Asia, forming the great belt of the Eurasian steppe. They form the tall grass prairies of America and are probably developed in parts of South America as well. Their main agricultural use is for wheat growing, and they form the wheat soils of the world. The climate is too dry for crops other than wheat and some sorghums to be grown profitably, and their management has already been discussed in the section on dry farming in Chapter 22.

The chestnut soils are developed under still more arid conditions than the black earths. Their name describes their colour, the colour of the skin of the edible chestnut, *Castanea sativa*, not the horse-chestnut, *Aesculus hippocastanum*. They are formed under conditions where the potential transpiration exceeds the rainfall, so at no time in the year does water leach out of the profile. The effect of the increasing lack of water is to give a grass vegetation with a shorter root system and a smaller annual production of organic matter,[1] so that both the depth to which the organic matter reaches, and its content at each depth, decreases. At the same time the layers in which the calcium carbonate and gypsum are deposited come closer to the surface.

As the climate becomes still more arid, shrubs begin to form an important part of the vegetation, but the production of organic matter both above and below ground becomes small, so that the organic matter content of the soil rapidly decreases, and what is there becomes increasingly concentrated in the superficial layers. The colour of the soil also lightens, becoming first brown and then grey, giving the sierozem or grey desert soils of the Russians.

The effect of increasing temperature on these grassland soils is threefold. In the first place, the colour of the soil reddens, and this is true for the prairie, chernozem and chestnut soils.[2] In the second place the horizon of calcium carbonate deposition may both thicken and harden, becoming a band up to several feet thick. This is known as caliche in parts of America, and *kankar* in parts of India and is also well seen in many parts of the Mediterranean.[3] If these desert soils are

[1] H. L. Shantz, *Ann. Assoc. Amer. Geog.*, 1923, **8**, 81.

[2] J. Thorp and M. Baldwin, *Ann. Assoc. Amer. Geog.*, 1940, **30**, 163.

[3] For a description of this in the black cotton soil area in India, see D. Singh and G. Lal, *Ind. J. Agric. Sci.*, 1946, **16**, 328; in the Mediterranean, G. Gaucher, *C.R.*, 1948, 227, 154; G. Aubert, *C.R. Conf. Pédol. Méditerr.*, 1948, 330; in New Mexico, J. H. Bretz and L. Horberg, *J. Geol.*, 1949, **57**, 491.

over-grazed, so erosion takes place, these bands become exposed on the surface of the desert, giving a hard pavement. In the third place the organic matter decreases, presumably because of the higher temperature giving a high rate of decomposition. Conversely, when chernozem soils extend into cooler regions their organic matter content increases.

Leached Soils of the Humid Tropics[1]

Weathering in the tropics is relatively a much more corrosive process than in the temperate regions, and the rain when it comes tends to fall in heavy storms, so that such factors as slight changes in topography or in permeability of the soil will cause much greater differences in the type of soil being formed than in the temperate regions. This has the consequence that the land surface in the tropics tends to be a mosaic of very different soil types and this is most pronounced in regions of relatively moderate rainfall.[2]

The parent material from which the soil is being derived is also of great importance, for if the land surface is relatively recent, or if for any reason unweathered rock particles are in the root zone of the vegetation, appreciable amounts of mineral nutrients will be released by the weathering of these particles with a consequent effect on the luxuriance of crops being grown on the land (see p. 503 for example). And this effect again is much more noticeable in the tropics because of the much greater intensity of weathering. On the other hand, if the soil is formed on a crust of weathering on an old land surface, which commonly occurs over much of the tropics, the crust will only contain secondary minerals, which are present there because they are extremely resistant to weathering by downward moving water. Hence soil forming processes can have little effect on the minerals in the crust.

A characteristic of the humid tropics, and the tropics with a fairly long rainy season each year is the enormous rate of growth, and in natural conditions of decomposition, of the vegetation. Thus P. E. Vageler estimates that tropical rain forests may produce over 100 tons per acre of vegetable matter, a figure comparable to G. ap Griffith's finding that in parts of Uganda elephant grass (*Pennisetum purpureum*), which requires a moderately well distributed rainfall, may produce 60–100 tons per acre of vegetable matter, containing 10–16 tons of dry matter and 600–1,000 lb. of nitrogen. Yet in well-drained tropical

[1] For more detailed discussion on these soils, see P. E. Vageler, *Grundriss der tropischen und subtropischen Bodenkunde*, 2nd ed., Berlin, 1938, and *An Introduction to Tropical Soils*, London, 1933; H. Erhart, *Traité de Pédologie*, 2 vols., Strasbourg, 1935, and 1937; E. C. J. Mohr, *The Soils of Equatorial Regions*, translated by R. L. Pendleton, *Ann Arbor*, 1944; J. Thorp and M. Baldwin, *Ann. Assoc. Amer. Geog.*, 1940, **30**, 163; H. Jenny, *Soil Sci.*, 1948, **66**, 5, 173; *Proceedings of the First Commonwealth Conference on Tropical and Subtropical Soils* (1948), issued as *Tech. Comm.* 46 of *Commonw. Bur. Soil Sci.*, 1949; C. E. Kellogg and F. D. Davol, *Publ. I.N.E.A.C. Ser. Sci.*, 46, 1949.

[2] C. G. T. Morison *et al.*, *J. Ecol.*, 1948, **36**, 1.

rain forests there may only be a thin layer of dead and rotting but unhumified vegetation lying on the soil surface that may not be thick enough to cover the surface of the soil. In fact H. Jenny[1] found in such forests in Colombia that the weight of the forest floor lying on the soil was only about 2 tons per acre, although as the rainfall decreased so the weight of litter increased.

This dead vegetation is rapidly attacked by saprophytic organisms and though no quantitative estimates are available, it is probable that the soil animals play a relatively more important role here than in the temperate regions. Further, the organisms decomposing this dead vegetation do not produce humus, in the temperate sense of the word. The soil may contain very high amounts of carbon and nitrogen, but this organic matter has a much lighter colour, or may be almost colourless under natural conditions. Nothing is known about the composition of this material. Vageler states that it darkens on oxidation and drying; that it is probably water-soluble, and that it contains acidic groups; an isolated observation of M. V. Tracey[2] suggests that it may contain over 50 per cent of polyuronides. Thus the soil just below the forest floor may be very light in colour, a light yellow to brown, or may have a bright red colour, yet contain several per cent of organic matter. It seems to be generally true that the humus in all well-drained tropical soils is lighter in colour than in the temperate regions, and that many tropical soils with impeded drainage have an intense black colour although they may only contain small amounts of organic matter. Hence it is almost impossible to judge the organic matter content of the soils in these regions from their colour.

Another characteristic of many well-drained tropical soils on old land surfaces is their extreme poverty in plant nutrients. Such soils may carry luxuriant virgin forest but yet have almost all their supply of plant nutrients present in the living or dead plants and animals or their ephemeral decomposition products. Hence, once such land has been cleared of vegetation and a few crops taken and removed, all the plant nutrients will also have been removed and the soil left in a condition of extremely low productivity.

The outstanding feature of most chemical analyses that have been made on undisturbed well-drained soils in the humid tropics has been the uniformity in the chemical composition of the soil, the clay and the free sesquioxides down the soil profile.[3] In so far as the soil weathers it must dissolve away completely, leaving virtually no residue behind. The colour of the soils can be either red or yellow to brown. The red

[1] *Soil Sci.*, 1948, **66**, 173. [2] *Analyst*, 1948, **73**, 554.

[3] See, for example, F. Hardy and G. Rodrigues, *Soil Sci.*, 1939, **48**, 361, 483; F. T. Seelye *et al.*, ibid., 1938, **46**, 23 (for Samoa); J. A. Bonnet, ibid., 1939, **48**, 25 (for Puerto Rico); G. J. Hough, *U.S. Dept. Agric., Tech. Bull.* 548, 1937 (for Hawaii).

colour is probably developed under a climate having a hot annual dry season, whereas the yellow is more common either under a hot uniformly wet climate or under a hot climate in which the hot weather coincides with the rains and the cooler weather with the dry season. However, soils devoid of iron have a white to pale yellow or brown colour. The difference in colour is presumably due to the iron being present, limonite, hydrated FeO(OH), under normal humid conditions but being converted to haematite, Fe_2O_3, under hot dry conditions. But whenever the drainage is impeded, the yellow-brown colour is usually dominant.

There is evidence that typical podsols can be found in the hot, humid tropics. They have been described as occurring in permeable quartz sand carrying a heath vegetation with a thin layer of acid mor on the surface of the sand. There is usually up to 10 to 20 cm. of A_1 horizon, from 20 to 100 cm. of bleached A_2 sand, followed by a B horizon that is enriched with iron and aluminium and may be indurated. Table 125, taken from some work of H. J. Hardon,[1] refers to such a soil in the lowlands of Borneo. P. W. Richards[2] has given other examples of podsols under tropical heaths from other equatorial regions.

Podsols also occur in the uplands of tropical regions, at elevations of 6,000 feet or over, when the climate is no longer tropical and the mean annual temperature will be about 15° C. instead of 25° C. Under some forest conditions the various layers in the profile can be very thick, and both Jenny and also Thorp and Baldwin have noted light coloured A_2 layers up to 3 feet thick.

TABLE 125

The Composition of a Lowland Tropical Podsol from Bangka, Borneo

Horizon	A_0	A_1	A_2	B_1	B_2
Depth in cm.	0–10	10–25	25–40	40–70	70–100
Colour	black	greyish black	greyish white	dark brown	light brown
pH	2·7	3·9	6·1	3·9	4·6
Per cent clay	—	1·6	0·6	7·2	4·6
Analysis of Clay Fraction:					
SiO_2	48·9	60·6	65·2	18·2	14·0
Al_2O_3	18·8	12·3	10·1	70·7	73·2
Fe_2O_3	6·4	3·1	4·2	4·4	6·5
TiO_2	10·1	14·2	8·6	2·7	2·7
$\frac{SiO_2}{Al_2O_3+Fe_2O_3}$	3·62	7·17	8·64	0·42	0·31

[1] *Pedology*, 1938, 325. Note the profile described by him in *Natuurwet. Tijdsche Ned. Ind.*, 1936, **96**, 25, and quoted in the seventh edition of *Soil Conditions* as an example of a tropical podsol, refers to a profile at an elevation of 2,000 m. where the average daily and annual temperature is 14° to 15° C. The mean annual temperature at Bangka is about 26° C.

[2] *Nature*, 1941, **148**, 129; *J. Ecol.*, 1936, **24**, 1.

CHAPTER XXXI

THE INFLUENCE OF TOPOGRAPHY ON SOIL FORMATION

Effect of Impeded Drainage and Ground-water on the Soil

WELL DRAINED SOILS are characterised by downward leaching of oxygenated water, hence oxidising conditions occur throughout the profile for at least the greater part of the year. But once the downward movement of water becomes impeded, so the micro-organisms and plant roots in the soil use all the oxygen in the water as fast as it is renewed, then reducing conditions set in. It is not that impeded drainage or high ground-water necessarily give reducing conditions; there must also be an agent in the layer of water-logging that not only removes oxygen from the water, but actually creates an oxygen deficit; and micro-organisms decomposing organic matter in this layer are the normal agents creating this deficit.

The effect of reducing conditions in the soil is for the accessible trivalent iron and tetravalent manganese among the metals to be reduced to the divalent condition, and for sulphates and nitrates to be converted to sulphides and ammonia. The effect of lowering the valency of the iron and manganese is to increase their solubility in the soil solution, for divalent iron can have a higher ionic concentration in the soil solution than trivalent, and divalent manganese is a simple cation whilst the tetravalent forms part of the very insoluble manganese dioxide. The effect of reducing sulphates to sulphides is to limit very sharply the amount of microbial and plant root activity in the layer, for sulphides are very toxic to most plant roots and only a restricted number of anaerobic micro-organisms can flourish in their presence.

Soils with impeded drainage are characterised by much of the iron and manganese being mobile, as well as some of the silicon, but the aluminium remains immobile,[1] as it cannot be converted to a soluble form by reduction. Movement of aluminium is therefore more characteristic of well-drained than badly-drained soils, and differs markedly from iron and manganese in this respect.

Impeded drainage and ground-water have another effect on the soil, for impeded drainage reduces the loss of the products of weathering from the soil, and both impeded drainage and high ground-water may

[1] R. S. Holmes *et al.*, *U.S. Dept. Agric., Tech. Bull.* 594, 1938; I. C. Brown and J. Thorp, ibid., 834, 1942.

actually allow products of weathering produced higher up in the soil profile, or from the soil or crust of weathering on higher ground, to accumulate. Hence, soil layers subject to high ground-water or impeded drainage are typically only slightly acid or neutral, and the exchange complex mainly contains either calcium alone or mixed with a considerable proportion of magnesium. These soils also often have the same content of exchangeable bases down the profile, whilst well-drained soils usually have a higher content in the surface layer, which is enriched with organic matter, than in the lower layers. Soluble silica also collects in this layer, particularly if ground-water is entering the area, so that if any clay is formed it is of the montmorillonite type. This can be particularly well seen in tropical areas having a pronounced wet and dry season, where the soil has only a limited permeability. The soil in all the small depressions is black and some of its clay is beidellite or montmorillonite, and the soil on all the small hillocks is red and the clay mainly kaolinitic.[1]

Impeded drainage or high ground-water can have another consequence in arid basins draining more humid hill or mountain land, for the ground-water is enriched in the products of weathering of the uplands, and as it evaporates it leaves behind the soluble salts it contained when it entered the basin. In this way soils can become so enriched in salts that most plants cease to grow. But salt soils and problems connected with the control of saline ground-water are so important in irrigation practice that they will be dealt with in Chapter 33.

The outstanding visual characteristic of soil layers in which strong reducing conditions prevail is the colour of the soil, for it is a light grey colour tinged with blue or green, presumably due to the ferrous iron present, though what these compounds are is not known, for the colour does not readily become brown on drying or when exposed to the air, and it persists for a long time after the field has been drained. It is soil layers with this colour that are called glei, or gley, a Russian peasant word for this soil. The chemical characteristics of gley horizons[2] are, as already mentioned, that they are neutral or only mildly acid, they contain ferrous iron, much of it as exchangeable ions,[3] but some in other combinations that have not been identified, and they are usually low in phosphates.[4] The cause of the disappearance of phosphates from these layers is not understood, but it is probably connected with the reduction of iron from the tri- to the divalent state.

[1] G. Nagelschmidt, A. D. Desai and A. Muir, *J. Agric. Sci.*, 1940, **30**, 639.

[2] For a full account of these, see A. A. Zavalishin, *Glinka Mem. Vol.*, Leningrad, 1928; for an English summary of this paper, see J. S. Joffe, *Soil Sci.*, 1935, **39**, 391.

[3] V. Ignatieff, *Soil Sci.*, 1941, **51**, 249; A. A. Zavalishin *et al.*, *Probl. Sovet. Pochvoved.* 1940, **11**, 189.

[4] R. Glentworth, *Nature*, 1947, **159**, 441.

V. M. Goldschmidt and A. Muir[1] have pointed out that this reduction appears to release mobile phosphate although ferrous phosphate itself is insoluble.

But soils having impeded drainage, or subject to the influence of ground-water, usually have a zone that is only subject to reducing conditions for part of the year, and to normal oxidising conditions for the remainder. Thus, in many parts of the temperate regions, reducing conditions occur nearer the soil surface in the winter six months, when plant growth is very limited, than in the summer six months, when transpiration is active. These conditions of alternating oxidation and reduction have a great influence on the distribution of iron and manganese in the soil, for they tend to accumulate in this layer. During periods of reduction, divalent iron and manganese tend to move into this layer, usually from below, and then be oxidised in the subsequent period of oxidation; and the tendency is for more iron and manganese to move into this layer than out of it. The first effect of this is for the soil in this layer to become mottled or flecked with grey and yellow, the grey being the areas where reducing conditions still prevail, and the yellow being the deposits of ferric hydroxides.

As this process of iron and manganese accumulation proceeds, the pore space between the soil particles becomes increasingly filled with the iron and manganese deposits, and a definite indurated layer is formed which may become a continuous hard pan and which restricts drainage even more. On the whole, this pan formation is more pronounced the more permeable the soil, probably both because oxidising conditions can set in more quickly in summer and also because organic matter can wash down more easily, so that stronger reducing conditions can be set up during its decomposition. As the temperature increases, so the pan tends to become harder, although there also appears a tendency for it to develop more as concretions than as a uniform pan. These concretions are black to brownish black in colour, high in iron and often in manganese, and containing soil particles embedded in this cement.[2] Further, as the iron pan thickens, so usually does the material below the pan lose so much iron that its colour lightens. These pans, when well developed in the tropics, form the ground-water laterites discussed on p. 507.

Impeded drainage and ground-water have a marked effect on vegetation as soon as they cause reducing conditions in the root zone of the plants, for reducing conditions are very inimical to root development,

[1] Thorpe's *Dictionary of Applied Chemistry*, **8**, 151. They quote a paper by W. Einsele, *Arch. Hydrobiol.*, 1938, **33**, 361, who finds the same phenomenon in fresh water under reducing conditions.

[2] For analyses of concretions from Illinois podsols, see E. Winters, *Soil Sci.*, 1938, **46**, 33; for Oregon podsolic soils, C. C. Nikiforoff and M. Drosdoff, ibid., 1943, **55**, 459.

and they also slow up the rate of decomposition of the organic matter. Hence, they encourage shallow rooting and peat formation. Peat, like mor, accumulates on the surface of the mineral soil, but differs from it in the greater accumulation of certain of the organic fractions. There is, however, no sharp transition between peat and mor: as reducing conditions set in, so the number of species of organisms in the organic layer decreases, and so does the rate at which they decompose the more resistant fractions of the litter. Organic matter rich in lignin-like

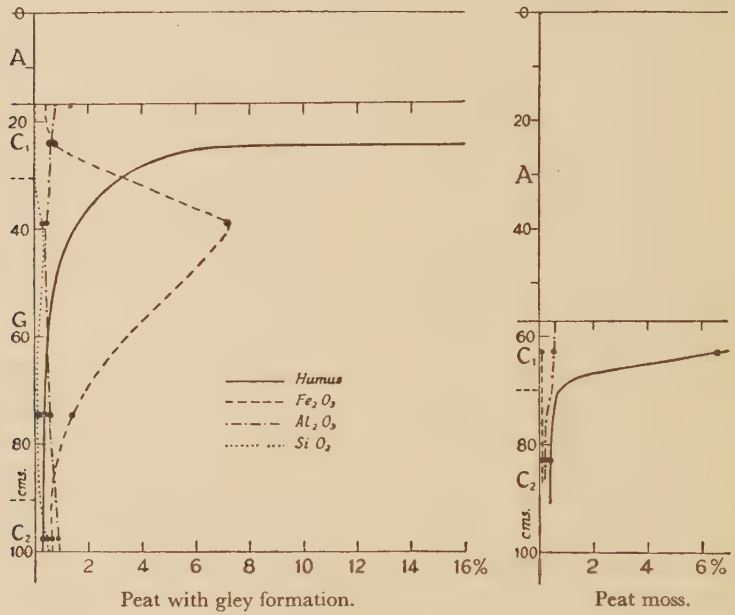


FIG. 47. Humus content and amounts of silica and sesquioxides extracted by the acid-oxalate method from two peat profiles.

The A layer in each profile represents the peat layer.

material and in hemicelluloses thus begins to accumulate, and the more prolonged the reducing conditions, the greater the thickness of the peat. If the peat layer is not too thick, so the ground-water level can fluctuate in the soil, a gley horizon develops under the peat in which iron accumulates, as shown in Fig. 47,[1] and this may become hardened to give the iron-ore concretions typical of many of these bogs. If, however, the peat thickens too much, because the soil underneath remains permanently water-logged, there is no means for the iron to move and no such accumulation takes place, as is also shown in Fig. 47. These effects can be illustrated by the transitional soils between the

[1] From O. Tamm, *Medd. Skogsförsöksanst.*, 1932, **26**, 163.

well-drained podsol under mor and the peat moss that develop as the ground-water level rises. The A_1 horizon begins to deepen at the expense of the A_0 or mor, due perhaps to grasses and herbs replacing the trees and returning more organic matter into the soil itself, in the form of fine extensive root systems, than the trees.[1] At the same time the amount of organic matter deposited at the top of the B_1 horizon increases and gleying becomes noticeable a little distance below the base of B horizon. These changes convert the well-drained podsol—Frosterus' iron podsol—first to his iron-humus podsol then to his humus podsol.[2] These various types of podsol can, however, occur very close to each other in the field, apparently without the ground-water conditions showing striking differences, so it is possible that changes in ground-water level are not the only ones that can convert an iron into a humus podsol. As the ground-water, or gley horizon, rises still more, so the A_0 horizon thickens, the A_1, A_2, and B thin, and the translocation of humus and sesquioxides becomes less, giving first the peat podsol, then the gleyed peat and finally the peat moss. The profile changes from the iron to the peat podsol are shown diagrammatically in Fig. 48, and the distribution of humus and the oxalate soluble iron and aluminium in the iron and iron-humus podsols have already been given in Fig. 46 on p. 519 and in the peat podsol and peat moss in Fig. 47.

Soils in a small region formed on a common parent material have been separated into four groups by J. H. Ellis.[3] He introduced the words *oromorphic* to describe well-drained coarse sands and gravels incapable of holding much water, *phytomorphic* for well-drained loams and clays which hold a considerable amount of water when wet but drained, *hydromorphic* for soils severely affected by ground-water and *phyto-hydromorphic* for soils having impeded drainage. Ellis[4] himself, in Manitoba, and R. Glentworth[5] in Scotland have shown the value of terminology in classifying and mapping soils in regions where the drainage conditions are more variable than the parent material.

Pan Formation in Soils

Many types of pan can develop in the soil: the iron-humus hard pan, or indurated horizon, that sometimes develops in well-drained podsols, the iron-manganese hard pan that develops under conditions of fluctuating water table, and the clay pan can all be found in humid or semi-arid climates. In hot arid climates pans due to calcium carbonate (p. 529), and gypsum can occur, and in some hot climates with a

[1] H. Pallmann, A. Hasler and A. Schmuziger, *Bodenk. PflErnähr.*, 1938, **9**, 94.
[2] For an early discussion of these types of podsol, see B. Frosterus, *Geol. Komm. Finland, Geoteck. Medd.* 14, 1914.
[3] *Sci. Agric.*, 1932, **12**, 338. [4] *The Soils of Manitoba.* [5] *Trans. Roy. Soc. Edinb.*, 1944, **61**, 149.

pronounced dry season, pans may also be due to silica cementing soil particles together. C. C. Nikiforoff and L. T. Alexander[1] have given an example of such a silica pan from California, and E. Winters[2] of one from Tennessee. They are presumably due to some of the mobile silica in the soil solution, which has been produced by weathering during the wet period, being precipitated as a cement, instead of as secondary quartz, during the dry. However, A. K. Dutt[3] considers that this silica cementation only occurs when the clay is of the non-swelling kaolinite type and not of the swelling beidellite or montmorillonite type.

The clay-pan soils develop on level plateaux that have been subjected to weathering for a sufficiently long time, and they are known as planosols in America. The mechanism of the formation of clay pans has not yet been agreed. The first problem that needs an answer is the proportion of clay forming the pan that has been synthesised *in situ* to the proportion that has been washed into it from above. There seems little doubt that much of the clay in a clay-pan profile has been formed in the profile, because there is more clay in the profile in proportion to the sand fraction than in the parent material, but there is little conclusive evidence of the proportion of the clay that has been formed in the pan to that translocated into it from above. Some recent results of C. E. Marshall[4] and his co-workers illustrate the present state of our knowledge. They worked with Missouri prairie soils developed on a silty loam loess. They found that in one soil profile a column of soil 1 sq. cm. in cross-section and 1·6 m. deep contained 68 gm. of clay, and they estimate that before weathering it would have contained only 57 gm., so that 11 gm. of clay have been formed during the weathering process. In addition, they estimate that 11 gm. of clay were washed out of the top 45 cm. of soil and 22 gm. were gained in the next 65 cm. There is no means of estimating how much of this extra 22 gm. is represented by the 11 gm. lost by the upper layer, how much represents clay formed in the upper layer and translocated into the clay pan, and how much was formed in the clay pan itself. Translocation was probably responsible for most of the 11 gm. lost by the upper layer because it also lost 11 gm. of silt, all of which appeared in the clay pan. But they further showed that the clay in the clay pan does not merely fill the interstices between the silt and sand particles, it increases the average distance between neighbouring sand and silt particles, and in fact they found that the soil volume containing a sand

[1] *Soil Sci.*, 1942, **53**, 157.
[2] *Proc. Soil Sci. Soc. Amer.*, 1943, **7**, 437.
[3] *Soil Sci.*, 1948, **65**, 309.
[4] With E. P. Whiteside, *Missouri Agric. Expt. Sta., Res. Bull.* 386, 1944; with J. F. Haseman, ibid., 387, 1945.

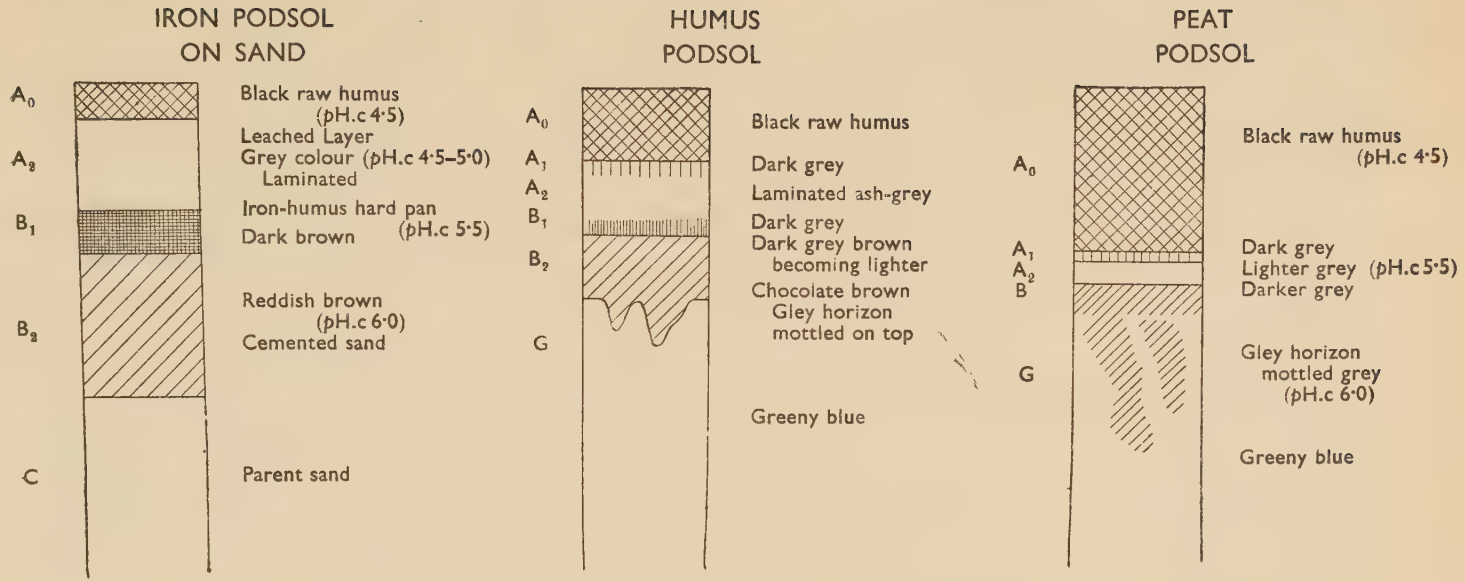


FIG. 48. Diagrammatic sketches of podsol profiles.

particle increased by 50 per cent in the centre of the pan compared with that in the undisturbed soil. In another two profiles, they fractionated the clay at the various levels and showed that the principal gain in clay in the pan was in particles smaller than 0·5 μ, which were principally composed of a beidellite type of mineral. There was some translocation, but little formation of coarse clay particles, which were composed of quartz, felspar, kaolinite, illite and beidellite.

The second problem in clay-pan formation is the mechanism which causes the precipitation of the clay in what is to become the clay pan if translocation of clay from the upper layers is important. It is possible that if clay-pan formation starts with clay forming in the interstices in the pan, then clay particles that are being translocated downwards are only stopped in this layer when it is sufficiently dense to filter them out of the downward-percolating water. But if the clay is precipitated in this layer it is probable that the mechanism is somewhat as postulated by H. Jenny and G. D. Smith,[1] who showed that clay pans could be built up in a coarse grained system such as sand or glass beads if an electropositive iron sol and a clay suspension were alternately allowed to percolate through the system. They also showed that if humic colloids were mixed with the clay, no pan was formed.

The formation of the iron-manganese concretions and the iron pan under fluctuating ground-water is again not fully understood. Under many conditions the precipitation of the iron and manganese takes place on concretions already existing, so that the most favoured sites for iron and manganese precipitation is on iron and manganese oxide or hydroxide surfaces. The concretions have been analysed by E. Winters[2] and by M. Drosdoff and C. C. Nikiforoff,[3] who showed that the smaller the concretion the higher its iron content, provided the concretion was above a certain minimum size, and the larger the concretion the higher its manganese content. The iron was nearly all soluble in Truog's iron solvent, so was present probably mainly as limonite $Fe(OH)_3$, with perhaps some Fe_2O_3, but the form of the manganese was not determined. The concretions contained between 5 and 17 per cent of iron and 0·5 to 8 per cent of manganese, which for manganese might be a hundred times higher than in the soil itself. The cause of the mobility of the iron and manganese is, as already pointed out, the alternations of reducing and oxidising conditions, causing the metals to be present as simple divalent cations during the reducing periods and in insoluble unionised compounds during the oxidising.

[1] *Soil Sci.*, 1935, **39**, 377; *Missouri Agric. Expt. Sta., Res. Bull.* 210, 1934.
[2] *Soil Sci.*, 1938, **46**, 33.
[3] *Soil Sci.*, 1940, **49**, 333.

TABLE 126

Analytical Data for a Brown Earth Profile

Depth in cm.	0–10	20–30	30–40	90–100
pH	5·26	5·35	5·24	5·36
Clay, per cent	16·25	14·87	8·87	5·85
Exchangeable Ca (m.-eq.)	3·2	2·4	1·2	0·6
Exchangeable H (m.-eq.)	9·7	5·9	3·6	2·4
Composition of clay fraction—				
SiO_2/R_2O_3	1·51	1·45	1·03	0·86
SiO_2/Al_2O_3	1·93	1·92	1·59	1·16
Al_2O_3/Fe_2O_3	3·64	3·08	2·70	2·86
Acid oxalate Fe_2O_3, per cent	0·64	3·00	0·69	0·43
Acid oxalate Al_2O_3, per cent	0·55	1·75	0·64	0·44
Organic carbon, per cent	2·93	1·88	0·85	0·31
Organic nitrogen, per cent	0·119	0·097	0·05	—
C/N	24·6	19·4	17·0	—

Soil Formation on Hill Slopes

Soils on hill slopes differ from those on level ground both because the percolating water will tend to move laterally across the profile instead of merely downwards, particularly if there is any layer of low permeability in the profile, and also because the surface soil will be subject to erosion. The soil profile will therefore lose less bases than that on level ground, as the percolating water will be enriched in bases from the higher ground, and the soils will correspondingly be less acid. Thus, in areas where podsols under mor develop on the flat, brown forest soils under mull tend to develop on the slopes. Table 126[1] gives the analysis of such a soil developed on a 20° slope in a podsol region. The only indication of podsolisation is that the acid oxalate extract showed that iron and aluminium are being precipitated in the 20 to 30 cm. layer, although this was not apparent either in the amount of clay present or its sesquioxide content.

Soils on slopes are also liable to erosion, and this movement of soil down the slope may be of considerable importance even for slopes between 5° and 10°, for it will prevent the development of a strongly leached surface soil.[2] When the slope exceeds about 10°, actual creep of the whole soil down the slope may become sufficiently important to mask any effect of weathering due to the percolating water.

[1] A. Muir, *Forestry*, 1935, **9**, 116.

[2] G. W. Robinson, *Nature*, 1936, **137**, 950; G. Milne, ibid., 1936, **138**, 548.

The Soil Catena

The separate effects of topography just discussed cause soil formation to follow a fairly definite pattern according to the topography of the site, whenever the parent material and the climate do not change appreciably over the area. On extensive plateaux and peneplains, where percolation is downward and erosion abnormally slow, clay-pan formation, or planosol soils are characteristic, and since this causes impeded drainage, hard pans may also develop. On the top of hillocks and on the edge of plateaux, where percolation is good and normal erosion takes place, the well-leached soils are developed, and clay-pan and hard-pan formation is usually restricted. On the slopes percolation water enriched in bases and soluble products of weathering leaches across the profile, preventing the formation of profiles characteristic of purely vertical drainage, and pan formation is again rare. At the base of the slopes the products of weathering tend to collect, the soils are neutral, a montmorillonitic type of clay forms, and drainage may become impeded. Further, hard pans may also develop due to a fluctuating ground-water table.

This succession of soil type is so characteristic of land forms with only moderate relief that G. Milne[1] used the word catena to include the whole sequence of soil types that are developed from the water divide to the valley. He initially introduced this concept as a reconnaissance mapping unit, but it was soon found to be very valuable for grouping together in systematic form the individual soil series, recognised by the soil surveyors in the field, that were related to each other in this way. It therefore includes the method introduced by J. H. Ellis (p. 537) for grouping together the soils of a small region that differ mainly in their goodness of drainage. Milne himself has given examples of these catenas in Tanganyika,[2] H. Greene[3] and C. G. T. Morison *et al.*[4] in the Anglo-Eygptian Sudan, R. S. Holmes *et al.*[5] in the south-east, and I. C. Brown and J. Thorp[6] in the north of the United States. In hot, humid or semi-humid regions the leached soils are red, particularly in the subsoil, and as drainage becomes impeded so the colour changes through yellow to grey.[7]

Tropical and subtropical catenary soil sequences differ from those in temperate regions in that the *p*H of the soil on the plateau decreases as the drainage becomes poorer in the warmer, but increases in the cooler regions. The reason for this difference is that weathering goes

[1] *Soil Res.*, 1935, **4**, 183; *Trans. 3rd Int. Congr. Soil Sci.*, Oxford, 1935, **1**, 345.
[2] *J. Ecol.*, 1947, **35**, 192. [3] *Soil Res.*, 1939, **6**, 325. [4] *J. Ecol.* 1948, **36**, 1.
[5] *U.S. Dept. Agric., Tech. Bull.* 594, 1938. [6] *U.S. Dept. Agric., Tech. Bull.* 834, 1942.
[7] The bulletin of Holmes *et al.* gives a colour plate of these colour changes in the profiles of the Norfolk catena.

faster in the warmer climate, so that a montmorillonitic type of clay is formed having, in consequence, a high base exchange capacity, and therefore a low *p*H when unsaturated, whilst in the cooler climate much less of this is formed and more of the kaolinite and illite types, which have a lower base exchange capacity and hence a higher *p*H when unsaturated.

The effect of drainage on clay type and soil colour can be seen all over the tropics wherever the rainfall is high enough to ensure some leaching. Even quite small changes of relief are enough to give the change from red soils with kaolinitic clay in the better-drained areas to the black soil with montmorillonitic in the less well-drained depressions.[1]

Topography can have another effect on the soil and vegetation, for if changes of relief are sufficiently large, the climate becomes increasingly cool and humid as the land level rises. Hence, in the tropics and subtropics, mountain uplands have a climate, vegetation and soil more similar to the temperate than to the true tropical regions, but as one goes down to lower levels the climate becomes increasingly hotter, and usually increasingly drier also. Hence, the podsols and brown earths of the tropical highland give place first to the prairie, then the chernozem, then the desert and semi-desert soils of the arid lowlands on the one hand,[2] or, if the rainfall does not decrease, to the yellow, then red, and finally the black soils of the humid lowlands.

[1] See G. Nagelschmidt, A. D. Desai and A. Muir, *J. Agric. Sci.*, 1940, **30**, 639, for an example of this from Hyderabad.

[2] For examples of these changes, see J. Thorp, *Soil Sci.*, 1931, **32**, 283, for Wyoming; W. P. Martin and J. E. Fletcher, *Arizona Agric. Expt. Sta., Tech. Bull.* 99, 1943, for Arizona; R. H. Spilsbury and E. W. Tisdale *Sci. Agric.*, 1944, **24**, 395, for British Columbia.

CHAPTER XXXII

SALINE AND ALKALI SOILS

Saline Soils or Solonchaks

UNDER HOT, ARID conditions soluble salts accumulate in the surface of soils whenever the ground-water comes within a few feet of the surface, as may happen, under natural conditions, in the flood plains of rivers, the low-lying shores of lakes, and in depressions in which drainage water accumulates—in fact, in any region where marsh, swamp or other ill-drained soil would be found in humid regions. During dry periods the surface of these soils is covered with an efflorescence, or salt crust, which is dissolved in the soil water each time the soil is wetted.

Saline soils typically have an uneven surface, being covered with small puffed up spots a few inches high that are enriched in salts, for, as explained on p. 360 and as illustrated in Plate XXXI, salts congregate in the most salty areas because these areas remain moist longest after the onset of drought.

Saline soils normally show no change of structure down the profile, implying that the soil is barely affected by soil weathering and soil-forming processes; and such soils are known as solonchaks by the Russians and were called white alkali by E. W. Hilgard,[1] but are now usually called saline. Usually they are low in humus, because the natural vegetation cannot make much annual growth on them. The salts usually present in the soil are the sulphates and chlorides of sodium and calcium, though nitrates occur in a few places, and magnesium sometimes constitutes an appreciable proportion of the cations. Under these conditions, the *p*H of the soil is below 8·5 and the colour of the soil surface is light. However, under some conditions an appreciable proportion of the salts present may be sodium carbonate which will raise the *p*H of the soil to 9 or even up to 10. If other salts are only present in small concentrations, this sodium carbonate may cause the humic matter in the soil to disperse and take on a black colour, giving the black alkali soil of Hilgard, which will be discussed in the next section under the heading Alkali Soils.

Saline soils may contain over 100 tons per acre of salt in the top four feet of soil, that is, the salts may constitute over 1 per cent by weight of the soil, though many saline soils contain less than this. The natural vegetation on such soils has a very high ash content, up to one-quarter of

[1] *Soils*, New York, 1906.

the air-dry plant may be ash, and the greater proportion of the ash may be soluble salts, typically sodium chloride. Hence, the vegetation will also bring salts to the soil surface, but its effect is probably small, amounting to under 200 lb. per acre annually,[1] owing to the small amount of total growth made per year.

The source of the salts in natural saline soils is usually the ground-water, which is enriched with salts from two sources. Part, sometimes all, is derived from the weathering of rocks in the upper reaches of the river, and part is sometimes derived from salt deposits laid down in early geological periods in strata through which the ground-water moves. Saline soils have also been produced artificially by faulty irrigation, for irrigation always involves putting salts on the land as well as water. Hence, salt control is a fundamental part of irrigation and will be discussed in detail in the next chapter.

Alkali Soils: the Solonetz and Solod

When the water table in a natural saline soil falls, so that salts no longer accumulate in its surface, the rain-water washes the salts that were there down the profile, and this process sometimes causes considerable chemical changes to take place in the profile. If the salts are predominantly calcium, or if during the process of washing out over 90 per cent of the exchangeable ions remain calcium, then the saline soil is converted into the steppe or semi-desert soil appropriate to its region.

Much more radical changes in the surface soil take place if the calcium reserves in the soil are so low that, during the washing out of the salts, an appreciable proportion of the exchangeable calcium ions are replaced by sodium. Sodium ions only need to constitute 12 to 15 per cent of the exchangeable ions to reduce the water stability of the soil structure sufficiently for the clay and humic particles to disperse. This harmful effect is accentuated by sodium carbonate being formed in the soil solution during the final stages of the washing out of the salts, causing the *p*H of the soil solution to rise, often above 9, and consequently increasing the ease of dispersion of the fine particles.

For a long time the source of the sodium carbonate produced during this washing out was not understood, although P. de Mondésir[2] in 1888, and K. K. Gedroiz[3] in 1912, gave essentially the correct explanation. Carbonate and bicarbonate anions are being continually produced in the soil by the carbon dioxide given off by the plant roots and soil organisms, and these anions must be neutralised by cations or

[1] V. A. Kovda, *Pedology*, 1944, Nos. 4–5, 144.
[2] *C.R.*, 1888, **106**, 459.
[3] *J. Expt. Agron.* (*Russian*), 1912, **13**, 363.

hydrogen ions. These cations will be obtained from the exchangeable cations in the exchange complex unless there are reserves of calcium carbonate in the soil. Hence, if there is an appreciable proportion of exchangeable sodium ions in the soil, enough will come into the soil solution to give what is in effect a solution of sodium carbonate strong enough to raise the *p*H of the soil to 9 or over.

These conditions of high alkalinity and low salt content lead to the clay and organic matter particles becoming deflocculated and the soil structure water-unstable. The soil surface becomes dark-coloured, often black, due to the dispersed humic particles; the surface typically dries into large, very hard, prismatic units having well-defined edges and smooth surfaces; and clay particles tend to wash down the profile, giving an incipient clay pan. Soils in this condition were called black alkali by Hilgard—he used this name without regard to the amount of other salts present—and they are extremely difficult soils to handle, for they are very plastic and sticky when wet and form hard compact clods when dry.

The second stage in the washing out of salts, when there is an appreciable proportion of exchangeable sodium in the exchange complex, is for clay and organic matter to move down the profile into the developing clay pan, with the consequence that the profile becomes banded rather like a podsol. The surface soil is dark grey, owing to the deflocculated humus, then comes a pale layer, and then another dark, very compact layer having a very sharply defined upper surface and merging gradually into the subsoil with increasing depth. The darker colour of the compact layer compared with the layer above it may be due to its higher clay content, for it does not always have a higher content of organic matter.[1] The top two layers have lost much of their clay, and have a loose, porous, laminar structure, whose upper surfaces may be paler than their lower, possibly because of silica being deposited on them. The clay pan cracks on drying into well-defined vertical columns having a rounded top and smooth, shiny, well-defined sides which can be broken into units about 10 cm. high and 5 cm. across with a flat base. Below this the columns break into rather smaller units with a flat top and bottom which on light crushing break up into angular fragments.

As the leaching of these desalinised soils proceeds, the upper two horizons deepen, and often become slightly acid in reaction. Gedroiz, who was one of the first to give a plausible account of the chemical consequences of the process, noticed that the content of amorphous silica in these horizons, and particularly in the top darker horizon,

[1] A. L. Brown and A. C. Caldwell, *Soil Sci.*, 1947, **63**, 183, give an illustration of this for well-leached Minnesota soils.

increased. The further development of these soils has not been worked out in detail, though some of B. B. Polynov's work suggested that the very characteristic clay pan becomes less pronounced, possibly because of sandy material from the A horizon washing down in the cracks between the structural units.

These soils are called solonetz in the early stages and solod in the later stages of their development by the Russians, and they have been extensively studied on the river terraces of southern Russia and Central Asia.[1] Gedroiz assumed that they formed under the influence of exchangeable sodium, as given in the account above, and this assumption has been accepted by many other workers. But there are large areas in western Canada and the United States[2] where soils having the morphology of these solonetz and solods are found, yet where sodium forms a very minor proportion of the exchangeable ions. It is possible that they originally contained over 12 per cent of exchangeable sodium, but that nearly all of this has now been lost by leaching. However, most of these soils that are now low in exchangeable sodium contain over 40 per cent, or even over 50 per cent, of exchangeable magnesium. It is, therefore, possible that if during the leaching out of soluble salts the exchange complex acquires a high proportion of exchangeable magnesium, the soils will partially deflocculate and undergo the same type of profile development as soils with a high proportion of exchangeable sodium. Hence, much more critical work must be done before one can decide just what changes can only be brought about by exchangeable sodium, and what by either exchangeable magnesium or other causes.

Unfortunately, the processes at work during the formation of solonetz and solod soils have not been critically examined by present-day techniques. Thus little is known about the weathering that takes place in the A horizons of these soils, or the source of the silica that can be dissolved by treating the soil with 5 per cent KOH—the method used to determine amorphous silica—or the movement of iron and aluminium hydroxides, if it takes place. Similarly, little is known about the clay in the B horizon, whether it was mainly leached down from the A, or whether it was mainly synthesised *in situ*. Even the type of clay in this horizon has not been investigated in detail. I. D. Sedletsky,[3] for example, claims to have isolated from Russian solonetz

[1] For some detailed Russian work, see K. K. Gedroiz, *Nosovka Agric. Expt. Sta., Bulls.* 38, 1925; 44, 1926; 46, 1928; D. G. Vilensky, *Salinised Soils*, Moscow, 1924; V. A. Kovda, *Solonchaks and Solonetz*, Moscow, 1937. J. S. Joffe, in his book *Pedology*, New Brunswick, 1938, has given a long summary of Gedroiz's and Vilensky's work.

[2] See, for example, W. P. Kelley, *Amer. Soil Survey Assoc.*, 1934, **15**, 45 (California); C. E. Kellogg, *Soil Sci.*, 1934, **38**, 483 (N. Dakota); C. O. Rost and K. A. Maehl, ibid., 1943, **55**, 301 (Minnesota); J. M. MacGregor and F. A. Wyatt, ibid., 1945, **59**, 419 (Alberta); C. F. Bentley and C. O. Rost, *Sci. Agric.*, 1947, **27**, 293 (Saskatchewan).

[3] *C.R. Acad. Sci. (U.S.S.R.)*, 1944, **33**, 308; 1937, **17**, 251.

a clay mineral characteristic of these soils which he called Gedroizite, and which he considers to be a vermiculite in which the magnesium is replaced by sodium and potassium. W. P. Kelley and his co-workers,[1] on the other hand, could only find an illite in the B horizon of the Californian solonetz-type soils they worked with, whilst A. L. Brown and A. C. Caldwell[2] found montmorillonite was the principal clay constituent in a number of acid solod soils, although some illitic clay was also found, particularly in the A layer.

It is interesting to guess at the minimum number of processes needed to obtain the solonetz-solod profile. Its characteristics appear to be a darker A_1 and B and a lighter A_2 horizon, a porous A and a compact B, and a clay pan breaking into columns having rounded tops. Most clay pans containing montmorillonite-beidellite type or illite type clays naturally crack into these columns on drying, except they usually have all their sides sharp. The rounded top is presumably due to the original sharp edges breaking away at the top, perhaps due to their water-instability, which in turn would be caused by them having much exchangeable sodium or magnesium in their complex. The B structure is, therefore, probably more characteristic of the clay mineral than of the exchangeable sodium or magnesium. The dispersion of clay in the A horizon and precipitation in an already formed clay pan below probably merely indicates the absence of salts and perhaps also requires low calcium. The formation of the A_2 horizon may only mean that the pores are wide enough to let humic matter pass, and the darker B due to them being so fine that it collects there. The process that seems to be characteristic of these soils, and needs detailed investigation before any specific theories can be formulated, is the formation of amorphous silica.

Under natural conditions, areas of saline and alkali soils usually contain a mixture of solonchak and solonetz, or solonetz and solod, or even all three together, depending on the relief of the area. The low-lying spots may be solonchak, those on moderate relief solonetz, and on higher ground solod; and differences in level of as little as 1 to 2 feet can have a great influence on the stage in the solonchak-solonetz-solod chain that the soil has reached.

Areas containing much solonetz soils may be very misleading to the inexperienced, for in some stages of development the dry soil is black and powdery and looks as if it ought to be fertile. It is only when wet, and particularly after heavy rain or irrigation, when water is held on the soil surface because of the impermeable B horizon that one realises how intractable they are. Some solonetz landscapes, however, are characterised by the surface being covered with shallow depressions

[1] *Soil Sci.*, 1941, **51**, 101. [2] *Proc. Soil Sci. Soc. Amer.*, 1947, **11**, 213.

from which the loose soil appears to have been removed, leaving the top of the B horizon uncovered. These depressions, known as slick spots or burn-outs in the Western States and Canada, are naturally extremely unfavourable for agriculture,[1] for the compacted clay pan is relatively rich in the montmorillonitic type of clay and has an appreciable proportion of exchangeable sodium or magnesium, hence is impermeable, plastic and sticky when wet, and hard when dry, never having a crumbly, mellow tilth.

[1] See, for example, R. Gardner *et al.*, *Colorado Agric. Expt. Sta., Tech. Bull.* 20, 1937; J. W. Fitts *et al.*, *J. Amer. Soc. Agron.*, 1939, **31**, 823.

CHAPTER XXXIII

THE MANAGEMENT OF IRRIGATED SALINE AND ALKALI SOILS

The Effect of Soluble Salts on Plant Growth

Soluble salts can have two types of effect on the growing plant: specific effects due to particular ions they contain being harmful to the crop, and a general effect due to them raising the osmotic pressure of the solution around the roots of the crop.

Specific effects fall into two classes: those operative at low and those at high concentrations. Of the former only two salts are normally of importance—sodium carbonate and soluble borates. The former may be harmful in itself, but its harmful effect is more likely to be due to the consequences of the high *p*H it brings about. Thus, many nutrients, such as phosphates, iron, zinc and manganese, become unavailable to the plant at these high *p*Hs on the one hand, and the soil structure tends to become water-unstable on the other, thus bringing about conditions of low water permeability, poor aeration and an unkind, almost unworkable tilth. Borates are directly toxic to the crop, and water containing as much as 1 part per million of boron, present as borate, depresses the growth of borate-sensitive crops, whilst water containing over 2 parts per million is unsuited for irrigation.[1]

Some ions may also have a toxic effect at high concentrations which enhances the harmful effect of mere concentration. Thus, some crops, such as peaches and beans, are damaged by chlorides in the soil solution at osmotic pressures at which sulphates do not harm them, whilst others, such as flax and some grasses, are more tolerant of chlorides than sulphates at equal osmotic pressures. Again, at equal fairly high osmotic pressures, magnesium ions are more toxic than calcium, and calcium may be more toxic than sodium, though these harmful effects have not been recognised in practice because in general sodium is a dominant ion in very saline soils. High contents of sodium ions sometimes appear to have a secondary harmful effect when they occur in soils very low in calcium, for then the crop will suffer from calcium deficiency.

The general effects of a high salt content in the soil is to give a dwarfed, stunted plant, but this is often not apparent in the field if there are no patches of low-salt soil to act as controls; and losses of

[1] For a discussion of this subject, with lists of boron-tolerant and boron-sensitive plants, see F. M. Eaton, *J. Agric. Res.*, 1944, **69**, 237; *U.S. Dept. Agric., Tech. Bull.* 746, 1941.

20 per cent or more of yield of the crop can be due to salts without salt damage being apparent to the farmer. As the salt content becomes higher the stunting becomes more noticeable, the leaves of the crop become dull-coloured and often bluish-green, and they become coated with a waxy deposit. Further, many crops growing in very saline soils do not display the symptoms of wilting very clearly, so they can be severely set back by lack of water before the farmer is fully aware of their suffering.

A high salt content around the roots of the plant markedly reduces their power of absorbing water. Thus, J. D. Newton,[1] as long ago as 1925, showed that the energy barley plants must expend to absorb water increases as the osmotic pressure of the solution in which they are growing increases, and H. E. Hayward and W. B. Spurr[2] have shown that maize roots absorb water at only one-third the rate from a solution of osmotic pressure 4·8 atm. as from one at 0·8 atm. Further, as already discussed on p. 374, the effective lowering of the free energy of the water in the soil is the sum of that due to the osmotic pressure of the soil solution and to the curved air-water menisci bounding its free surface, and the ease with which the plant root can extract water from the soil decreases as the free energy of the water in the soil decreases. Hence, raising the osmotic pressure of the soil solution is equivalent to raising the suction of the water held by the soil, but whether this is the sole cause, or only an important one, of the osmotic pressure reducing the rate of intake of water by the root needs further investigation, although the results given in Fig. 38 on p. 375 suggest that it must be the predominant factor.

O. C. Magistad and his co-workers at the Regional Salinity Laboratory at Riverside have recently published much work[3] on the relation between the osmotic pressure of the solution around the plant roots and the amount of growth the crop makes, and they concluded that, on the whole, there is a linear relation between the reduction in yield and the osmotic pressure of the solution, though, as shown in Fig. 38, the linear relation does not necessarily hold for crops sensitive to salts. Thus, H. G. Gauch and O. C. Magistad[4] showed that the yield of lucerne was reduced about 10 per cent for each increase of 1 atm. in the osmotic pressure. This factor naturally depends on the plant, for some are more tolerant of high osmotic pressure than others. Thus, beans growing in a solution of osmotic pressure 4·4 atm. only give 20 per cent, whilst cotton and sugar-beet give 70 per cent of their yields when growing in a 0·4-atm. solution.[5] Further increasing

[1] *Sci. Agric.*, 1925, **5**, 318.
[2] *Bot. Gaz.*, 1947, **105**, 152.
[3] See, for example, *Plant Physiol.*, 1943, **18**, 151, 556.
[4] *J. Amer. Soc. Agron.*, 1943, **35**, 871.
[5] O. C. Magistad and R. F. Reitemeier, *Soil Sci.*, 1943, **55**, 351.

the osmotic pressure reduces the amount of water transpired by the crop. F. M. Eaton,[1] for example, found that for a variety of salt-tolerant crops growing in sand culture at Riverside in solutions of increasing content of sodium sulphate, that the amount of growth made and of water transpired during a season were:

Osmotic pressure of solution in atm. .	0·7	1·8	3·5	5·1
Dry matter produced, kg. per 18 sq. ft.	11·4	8·9	6·3	3·7
Water transpired, thousand litres .	6·4	4·8	3·5	2·4

Eaton also showed that the cell sap of the plants maintained an osmotic pressure about 10 atm. higher than that in the culture solution, presumably due to the extra amount of salt taken up.

It is only since about 1940 that research workers have fully appreciated the significance of this effect of salts in increasing the effective suction of the water in the soil, and its consequences on the irrigated farm; for the greater the salt content of the soil, the less water the crop can remove from it before it begins to suffer from water shortage. Soils with a high salt content require therefore more frequent irrigation than similar soils of low salt content, and, as already noted, the crops growing on them do not wilt so plainly, so that it is more difficult for the farmer to see when an irrigation ought to be given. These two very important practical points have only recently been properly appreciated by agricultural advisers.

Plants differ in their powers in being able to withstand the harmful effect of salinity, or its consequences in the field. In the first place, as L. J. Briggs and H. L. Shantz[2] showed in 1912, plants have different abilities to extract water from soils in the wilting range, and the plants that are natural inhabitants of saline soils tend to have greater ability to extract water from soils at the drier end of this range. But no statement can yet be made about the existence of any correlation between tolerance to salts and ability to use water held at free energy depressions of, say, 15 atm. But not only must the crop be able to take water from the saline solution, it must also be able to take it quickly enough to maintain a proper transpiration rate if it is to make growth; and since one of the effects of the salt solution is to slow down the absorption of water by the roots, one would expect that plants would be more affected by a given salt concentration under conditions of high transpiration rates, that is, in hot deserts, than of low rates in cooler regions. This may be a valid deduction, but its field importance has not yet been established.[3]

In practice, salt tolerance is a very complex concept. The tolerance of a plant may be low when it is young but high when established—

[1] *J. Agric. Res.*, 1942, **64**, 357. [2] *Bot. Gaz.*, 1912, **53**, 229.
[3] For examples of its validity, see O. C. Magistad *et al.*, *Plant Physiol.*, 1943, **18**, 151.

lucerne is an example of this. The plant may be able to keep alive at high salt contents, but will make very little growth under these conditions and only grow slowly under moderate salt contents, and hence be of little commercial value—some of the alkali grasses are examples. Again, though the plant may be able to grow in fairly saline soils, the quality of the part harvested may be affected. Thus, cereals will grow and produce much green matter in soils too saline for them to produce any grain; sugar-beet growing in saline soils produces a root low in sugar which is difficult to refine; and forage crops may contain so much salts that they are unpalatable or injurious to livestock. Again, in practice, salt tolerance is often bound up with tolerance of alkali, high *p*Hs and low calcium on the one hand, and ability to withstand prolonged water-logging during irrigation, which is a common consequence of alkali, on the other. The effects of these various factors on the development of different crops are only now being examined. Hence, lists of salt-tolerant crops are still largely based on practical field experience in which these factors have not been properly separated out.

Recent American experience has graded crops into three categories: tolerant, moderately tolerant, and sensitive to salts, and an example of such grading is given in Table 127,[1] where plants are arranged approximately in order of salt tolerance in the fruit, arable and ley classes. Dates, sugar-beet, milo, cotton and some grasses fall into the tolerant group, and some of these are very tolerant of salts, whilst peas, beans and most clovers are in the sensitive group. But different varieties of a plant, particularly cottons and strawberry clovers, have been found to have different salt tolerances, so there is a possibility that plant breeders will be able to increase the salt tolerance of any particularly desirable crop. In the eastern Mediterranean countries potatoes, cowpeas and maize are considered salt-sensitive, and cucumbers, sunflowers and field-peas salt-tolerant, though why peas come into different categories in the Middle East and the Western States is not known. D. Stedman-Davies,[2] who gives this information, makes the important observation that adding nitrogen and phosphates to a soil may increase the resistance of the crop to salts. But, as already pointed out, salt tolerances will certainly be found to depend on climate, for the temperature in particular can strongly affect soil conditions which in turn affect the development and vigour of the root system.

Some information is now available about the amount of salt a soil can hold before the crops on it begin to suffer appreciably. O. C. Magistad and R. F. Reitemeier[3] showed that if the soil solution held at 15 atm.

[1] *Diagnosis and Improvement of Saline and Alkali Soils*, U.S. Regional Salinity Laboratory, 1947. See also *U.S. Dept. Agric. Yearbook*, 1943–7, and *Circ.* 707, 1944, for other similar lists.
[2] *Middle-East Supply Council, Agric. Rep.* No. 6, 1944.
[3] *Soil Sci.*, 1943, **55**, 351.

TABLE 127

The Relative Tolerance of Crops to Salts in the Western States of America

Good tolerance	Moderate tolerance	Sensitive
Date	Pomegranate	Grapefruit
	Fig and olive	Pear
	Grape	Almond
		Apricot and peach
		Apple and plum
		Orange and lemon
Sugar- and fodder-beet	Flax	Vetch
Milo	Sorghum	Pea
Rape and kale	Barley, oats, rye	Potato
Cotton	Rice	Bean
	Sunflower	
	Wheat	
Bermuda grass	Lucerne	Red and white clover
Rhodes grass	Sweet clover	
Rye-grass	Strawberry clover	
Western wheat grass	Sudan grass	
	Cereals for hay	

suction has an osmotic pressure less than 2 atm., that is, if it contains less than 0·4 per cent of dissolved salts, no crops suffer from salt trouble, but if the osmotic pressure at this suction is 10 atm. most crops suffer severely; and provided the soil solution does not contain appreciable amounts of sodium carbonate or borate, the composition of the salts is relatively unimportant compared with their effect on the osmotic pressure of the solution. The safe contents of salts in the soil can be expressed in other units. A soil is made up to about the sticky point with water, and then some of the solution removed by suction; if this solution contains up to 3,000 parts per million of salts, or has a specific conductivity at 25° C. of less than 4 millimhos per cm., no crop is likely to suffer from general salt injury, but if the salt content exceeds 5,000 parts per million, or the conductivity 8 millimhos per cm., then only salt-tolerant crops will grow, and even their yields are likely to be reduced, whilst if it exceeds 10,000 parts per million, or the conductivity exceeds 15 millimhos per cm., then no agricultural crops are likely to give economic yields.[1]

[1] *Diagnosis and Improvement of Saline and Alkali Soils*, U.S. Regional Salinity Laboratory. 1947.

The Control of Soluble Salts in the Soil

Irrigation water is continuously adding soluble salts to the soil which, unless they are continuously removed, must soon accumulate to such an extent that no crop can grow on the land. Thus, no irrigation scheme can last long that does not ensure that the salts brought into the surface soil are removed from the root zone of the crop as fast as they are brought in, and that the salt content at which this equilibrium occurs is low enough not to harm the crops appreciably. That this is, in fact, often very difficult to ensure can be appreciated from the fact that crop yields are said to be reduced by 10 to 20 per cent over much of the twenty million acres of irrigated land in the Western States of America by salts alone.

The general principles of salt control are to use water with as low a salt content as possible, to maintain the ground-water level at least 6 feet, and preferably deeper, below the soil surface, and to flush accumulations of soluble salts from the surface soil into the ground-water.

The salt content of irrigation water depends on its source. Mountain-fed rivers usually have low salt contents, rivers that have traversed desert countries usually have a moderate salt content, and springs and ground-water in the desert a high salt content. Table 128 gives the salt contents of some representative rivers actually used for irrigation, where the salts are divided up into sodium salts, very soluble salts, which, in addition, include magnesium salts as well as any calcium chloride, and total salts, which in addition include calcium sulphate and bicarbonate, and the table gives both the salt content of the water in parts per million, or milligrams per litre, and in tons per acre-foot. Since 3 to 4 acre-feet of water may be evaporated or transpired a year, this often involves leaving between $\frac{1}{2}$ to 4 tons of very soluble salts and sometimes much more behind in the root zone of the crop.

The problems of getting rid of these salts is obviously more difficult the higher the salt content of the water, the lower the rainfall, and the more impermeable the soil. Permeable soils with winter rainfalls of 10 to 15 inches will lose most of the salts they accumulated in the summer. But flushing down salts with rather salty irrigation water in rather impervious soils presents many difficulties, because this flushing must be done frequently, and during the process the soil is water-logged so that evaporation is proceeding rapidly and any crops growing on the land suffer from poor aeration. Further, the higher the salt content of the water, the greater is the proportion of the water that must be used for flushing, and therefore the smaller is the proportion that the crops can use for transpiration. Increasing salinity therefore puts down

TABLE 128

Salt Contents of River Waters Used for Irrigation

	Parts per million in water			Tons per acre-foot			Ratio
	Sodium salts	Very soluble salts[1]	Total	Sodium salts	Very soluble salts	Total	Ca/Na as equiv.
Colorado at Yuma, Arizona[2]	292	425	795	0·40	0·58	1·08	1·12
Gila at Florence Canal, Arizona[3]	664	772	1023	0·90	1·05	1·39	0·37
Pecos at Barstow, Texas[2]	3080	4110	6200	4·20	5·60	8·45	0·57
White Nile at Khartoum[3]	71	90	174	0·10	0·12	0·23	0·64
Murray at Cohuna, Victoria[4]	28	40	96	0·04	0·05	0·12	2·3
Indus at Sukkur[5]	12	99	300	0·02	0·14	0·41	16·0

the efficiency, or the duty as it is often called, of the water used. This need of water for flushing down salts may cause great administrative difficulties in areas where it is not fully appreciated,[6] for it means that often one-quarter to one-third of the water entering the area must be used solely for washing down the salts and not for growing a crop, and in consequence the maximum area that can be irrigated must be reduced by this fraction compared to the area that could be irrigated if no flushing was necessary.

This problem of flushing salts down into the subsoil emphasises the importance of fairly rapid drainage, so the land remains water-logged for as short a time as possible—for, as pointed out on p. 424, poor aeration, which is the consequence of water-logging, is more harmful at high than at low temperatures. But the water must also leach through the soil at a uniform rate all over the surface of the land, for otherwise salts will be leached out of some places but not out of others, and, as pointed out on p. 360, once an area begins to get a higher salt content than the surrounding soil, it tends to draw salts to it. Thus, it is essential the land shall be as level and as uniform as possible during irrigation so that the water has a chance to seep through the whole area as uniformly as possible. It is not difficult to ensure this uniform leaching if the rate of entry of the irrigation water into the soil lies in

[1] Excludes calcium sulphate and bicarbonate.

[2] Quoted by O. C. Magistad and J. E. Christiansen, *U.S. Dept. Agric., Circ.* 707, 1944.

[3] Quoted by F. W. Clarke, *Data of Geochemistry*, 1924. For more recent analyses of the South-western rivers of the U.S.A., see *Diagnosis and Improvement of Saline and Alkali Soils.*

[4] J. W. Paterson, *Victoria J. Agric.*, 1913, **11**, 298.

[5] H. P. Paranjpe, *Bombay Dept. Agric., Bull.* 96, 1920.

[6] For examples from the Punjab, see E. McKenzie Taylor and M. L. Mehta, *Indian J. Agric. Sci.*, 1941, **11**, 137; M. L. Mehta, *Punjab Irrig. Res. Inst. Publ.*, 1940, **3**, No. 4.

the range 0·3 to 3·0 inches per hour, but if it falls below 0·1 inch great difficulties arise if the irrigation water is at all saline.

The problems of drainage and keeping the water table low usually concern the engineers of the irrigation authority. It should be kept so low that its capillary fringe is below the main root zone, so that roots do not bring up soluble salts either into the herbage, nor concentrate them in the root zone. Thus, depths exceeding 10 feet are desirable, although under some conditions of impermeability the water may only be able to be removed from the subsoil by tile drains, and it is barely practicable to lay these deeper than 6 feet. But if the ground-water is not too saline it is often worth pumping it into the river or irrigation canals, diluting it with this better water and using this mixed water for irrigation lower down the valley. If this pumping is practised, so the ground-water is kept well below the surface, drainage is usually sufficiently good for no other precautions to be necessary.

It is of great importance to draw up a balance sheet of the salt and water movements in an irrigation area whenever possible, so that one can make an estimate of the net effect of present irrigation practice on the salt régime. C. S. Scofield[1] has done this for three areas in America, and his results for two, one lying immediately below the other on the Rio Grande River, are given in Table 129. In the Mesilla

TABLE 129

Annual Salt and Water Balance in Two Irrigation Areas of the Rio Grande (New Mexico and Texas)

Water in thousand acre feet. Salts and ions in thousand tons

Area under irrigation	Mesilla Area About 80,000 acres			El Paso Area About 120,000 acres		
	Entering	Leaving	Per cent retained	Entering	Leaving	Per cent retained
Water	774·4	496·1	33·3	496·1	173·2	65·1
Concentration of salts in water, tons per acre foot	0·805	1·226		1·226	2·666	
Total Salts	599·4	608·1	−1·5	608·1	461·8	24·1
Ca	80·6	69·7	14·5	69·7	41·3	40·7
Mg	17·6	15·5	11·9	15·5	10·2	33·9
Na+K	102·0	122·6	−20·3	122·6	111·7	9·0
HCO_3,CO_3[2]	93·9	80·5	14·3	80·5	28·2	64·9
SO_4	233·4	208·0	10·9	208·0	108·7	47·7
Cl	71·3	111·1	−55·8	111·1	161·4	−45·3
NO_3	1·4	1·5	−3·0	1·5	0·5	34·8

[1] *J. Agric. Res.*, 1940, **61**, 17.

[2] Computed as carbonate.

area, which lies above El Paso, the salts are in balance—the same weight is leaving the area as is being introduced—whilst in the El Paso area, which uses the water leaving the Mesilla area, salts are accumulating at the rate of about 150,000 tons per year, of which about 100,000 tons are calcium and magnesium carbonates and calcium sulphate, and 50,000 tons, or about 0·4 ton per irrigated acre are readily soluble salts.

The table also shows the important point that the composition of the salts leaving the area differs from that of those entering, for the water leaving is relatively richer in sodium and chloride and poorer in calcium and sulphate than that entering. In the next section it will be shown that the higher the ratio of sodium to calcium the less desirable is the water for irrigation; hence the greater the proportion of the water that has been derived as drainage water from schemes higher up the river, the more care may have to be taken with it because of its sodium content. In the actual areas given in the table both are losing chlorides, but the El Paso area is gaining sodium derived from the Mesilla area, and both are gaining calcium, and to a less extent magnesium, from the soils and rocks higher up the river.

The farmer possesses various methods for controlling the distribution of salts in the field. Even if he cannot get rid of them all, he can reduce their concentration in the surface by giving a heavy irrigation, and this is usually necessary in saline soils before seed is sown, for young plants are injured more easily than established ones by salts. Again, if a young plant is very sensitive to salts, or the salt content of the soil is high, sowing the crop at the beginning of winter, or of the cool season, when transpiration and evaporation are at their lowest for the area, gives the crop a chance of establishing itself in a soil of relatively low salinity. There is another method available for crops grown on ridges, which depends on concentrating the salts in certain parts of the ridge, leaving other parts less saline. If the land is thrown up into ridges and water runs between them, the salts can be concentrated on the top of the ridges, leaving the furrows and the sides of the ridge just above the water-line at each irrigation lower in salts. W. T. McGeorge and M. F. Wharton[1] have developed this method in the Salt River Valley of Arizona for lettuces, which are planted on the sides of the ridges just above the water-line. The salts accumulate as a white band above them, and even down to 12 to 24 inches below the surface the salts are lower under the furrow than under the area where the salts accumulate.

Thus, in summary, salts in the surface soil are controlled by flushing them down into the subsoil. Provided the soil is reasonably permeable

[1] *Arizona Agric. Expt. Sta., Bull.* 152, 1936.

and well levelled, no great trouble arises, but the more salty the water, the greater the proportion of the water is needed for salt control and the smaller the proportion that can be used for transpiration, also the more frequently must the field be irrigated. Trying to economise water under these conditions, by giving small irrigations that only wet the top 2 to 3 feet of soil, are bound to lead to increased salt concentrations in the soil surface. It is one of the most difficult problems facing agricultural advisers to work out methods for making the optimum use of a limited amount of rather saline irrigation water in arid districts within the social framework of the district.

The Control of Alkalinity

For an irrigation scheme to be permanent, not only must the total salt content of the soil be kept below a certain figure, but the proportion of exchangeable sodium in particular, and possibly also of exchangeable magnesium, in the exchange complex must be kept below certain limits. If more than 12 to 15 per cent of the exchangeable ions are sodium, difficulties may be experienced in keeping the soil permeable, and if more than 40 to 50 per cent are sodium, not only may these difficulties become very great, but the plant may no longer be able to take up sufficient calcium for its needs.[1] Soils containing a high proportion of exchangeable magnesium ions also have their permeabilities reduced and plants growing on them their calcium contents,[2] but to a considerably less extent than would be caused by a corresponding proportion of exchangeable sodium ions.

The principal cause of the proportion of exchangeable sodium ions increasing in the soil during irrigation is through base exchange between the sodium ions in the downward-percolating soil water and the exchangeable calcium and magnesium ions. Now calcium ions are held more tightly than sodium, and in dilute solutions it appears that very little exchange of sodium for calcium takes place in normal soils if the solution contains equal equivalent concentration of sodium to calcium, and little occurs if the sodium ions are twice, and under some conditions even three times as concentrated as the calcium.[3] But since the calcium ions are divalent and the sodium monovalent, at constant ratio of sodium to calcium ions in the percolating solution, the higher the actual concentration of sodium ions, the greater is their entry into the exchange complex, as explained on p. 113. Hence, higher sodium

[1] E. I. Ratner, *Soil Sci.*, 1935, **40**, 459; J. S. Joffe and M. Zimmerman, *Proc. Soil Sci. Soc. Amer.*, 1945, **9**, 51.

[2] N. V. Orlovsky and A. M. Kupstova, *Pedology*, 1939, No. 9, 73.

[3] W. P. Kelley *et al.*, *Soil Sci.*, 1940, **49**, 95; W. P. Kelley, *Cation Exchange in Soils*, New York, 1948; N. G. Cassidy, *Queensland J. Agric. Sci.*, 1944, **1**, 140.

to calcium ratios can be tolerated in irrigation waters of low than of high salinities. This can be seen from Fig. 49,[1] which shows on the right-hand curve the concentration and composition of salts in the percolating water that cause sodium ions to constitute 15 per cent of the exchangeable ions, and on the left-hand curve to constitute $7\frac{1}{2}$ per cent. Since soils containing over 15 per cent of exchangeable sodium usually have their properties very adversely affected by the sodium,

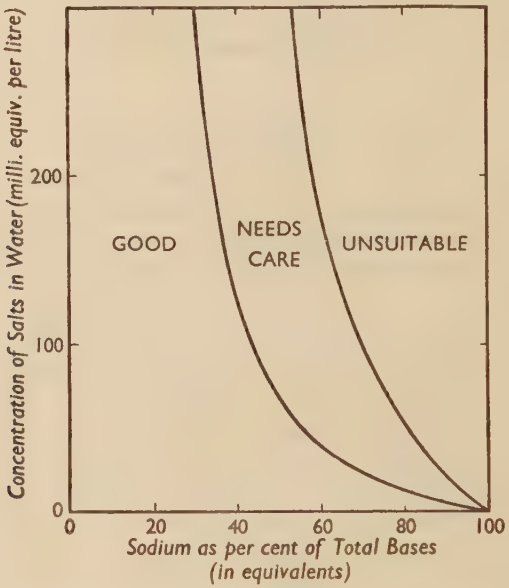


FIG. 49. The relation between the sodium content of water, its total concentration of salts and its suitability for irrigation.

waters lying to the right of the right-hand curve are unsuitable for irrigation, whilst if the exchangeable sodium constitutes less than $7\frac{1}{2}$ per cent of the exchangeable ions it has little effect on the soil properties, so that waters lying to the left of the left-hand curve are quite safe to use. Unfortunately the effective concentration of salts in the water is not that in the irrigation water itself, but that in the soil solution just before irrigation, for this is what leaches down on irrigation, and though this will be similar to the irrigation water on very permeable soils it may be up to ten times more concentrated in impermeable. Hence, the greater the impermeability of the soil, the lower must be the sodium content of the water for a given proportion of exchangeable sodium ions in the soil,

[1] Taken from H. Greene, *Using Salty Land*, F.A.O. Agricultural Studies No. 3, 1948. Other sets of curves are given in *Diagnosis and Improvement of Saline and Alkali Soils*.

Salt soils in the Karun delta, Iran. Note the way the salt efflorescences occur in separate patches

(*pp. 360, 544*)

Alternate strips of wheat and fallow near Monarch, Alberta
(*p. 571*)

Wheat stubble after being cultivated with the Noble cultivator

Noble cultivator used for stubble mulch cultivation

(*pp. 572, 580*)

Coffee bushes shaded by *Grevillia robusta* at Fort Ternan, Nyanza Province, Kenya
(*p. 587*)

and the more important it is that the proportion should remain low so the permeability, already poor, shall not be worsened.

Under present-day conditions when there is great pressure for increasing the acreage of land under irrigation, water must often be used that in time will cause the exchangeable sodium content of the soil to increase beyond the danger-point, if no precautions are taken to prevent it. Thus, water that is rather unsuitable for irrigation can still be used as long as the costs of keeping the exchangeable sodium down below a certain safe level are not too high. This involves, among other things, using the minimum possible amount of water for irrigation, to avoid unnecessary replacement of exchangeable calcium by sodium, though enough water must be used to wash down into the deep subsoil the salts that have accumulated in the root zone.

Exchangeable sodium can be replaced by calcium under field conditions either by adding a soluble calcium salt, such as gypsum, or a soluble acid such as sulphuric. Calcium carbonate is only useful if the *p*H is not too high, for whereas about 30 milli-equivalents of calcium as sulphate will dissolve in a litre of water, only about 1 milli-equivalent of calcium as bicarbonate or carbonate will dissolve at *p*H 8·6, though over 5 will dissolve at *p*H 7. Soils well supplied with gypsum can be irrigated with water that has too high a sodium content to be suitable for a gypsum-free soil.

Acids as such are not usually added to the soil, but powdered sulphur, which is rapidly oxidised in most arid soils to sulphuric acid, has been much used. Aluminium and iron sulphates have also been used, as both of these hydrolyse, leaving the hydroxide behind as a precipitate and liberating sulphuric acid. To obtain an idea of the amounts of these improvers needed, 1 ton per acre of sulphur will replace about 3 milli-equivalents of sodium per 100 gm. of soil from 1 foot of soil; and 5·4 tons of gypsum ($CaSO_4 . 2H_2O$), 6·9 tons of aluminium sulphate ($Al_2(SO_4)_3 . 18H_2O$), or 3·1 tons of calcium carbonate are equivalent to 1 ton of sulphur.

Routine methods of controlling alkali may thus involve the regular addition of an acidifying agent, in contrast to many humid soils which need the regular addition of calcium carbonate to counteract the normal increase of acidity due to leaching. If the soil is low in gypsum but well supplied with calcium carbonate it is always possible, in theory at least, to control the increase in exchangeable sodium, due to an unfavourable ratio of sodium to calcium in the irrigation water, by including in the rotation crops such as lucerne and some grasses that maintain a fairly high carbon dioxide content in the soil, since the solubility of the calcium in the carbonate increases rapidly with increasing carbon dioxide content. Farmyard manure and composts,

and probably composts containing sulphur, may also be useful, as they release carbon dioxide when mixed with the soil, but how far this is the main cause of their beneficial action on irrigated land, and how far it is due to them maintaining the permeability of the surface soil is not known.

In many irrigation schemes there are areas of land that have been rendered infertile by alkalinity and which can be reclaimed and brought back to cultivation. The principles underlying the reclamation of such areas are: firstly, to ensure that their drainage is adequate and that saline water is not seeping into them from higher ground; and, secondly, to replace some of the exchangeable sodium by calcium.[1] If the soil contains gypsum, draining the land and flooding it with water is probably all that is required, although if the soil is heavy, it may initially be sufficiently impermeable for the cropping to have to be chosen very carefully. But if the soil is low in gypsum, the primary trouble, which is either present, or which will develop unless precautions are taken, is the impermeability of the surface soil to water, and one great danger in reclamation that must be guarded against is increasing the impermeability of the soil during the reclamation. Soils containing much exchangeable sodium, or free sodium carbonate, will deflocculate and become quite impermeable to water if wetted with pure water, or with rain, whereas if they contain much soluble salts, or the irrigation water has a high salinity, they may remain flocculated and permeable. Hence, the second great principle in reclaiming alkali soils is to maintain a fairly high salt content in the soil during the process of leaching out the exchangeable sodium. Provided the soil remains permeable, drainage, adding gypsum or sulphur, and flushing down the salts will remove exchangeable sodium without difficulty.

Many disused alkali soils are, however, almost impermeable to begin with, and the improvement in permeability is the primary problem.[2] Typically this is done by replacing the exchangeable sodium in the surface layer and so stabilising it, and then deepening this stabilised layer. Adding gypsum to the surface soil, or on some lighter soils working in farmyard manure or compost, and then letting it wet and dry a few times will be enough to give a few inches of stable permeable soil. The soil may then be flooded, provided an adequate drainage system has been installed, to allow the gypsum to wash down slowly

[1] For illustrations of successful methods of reclamation, see W. P. Kelley, *J. Agric. Sci.*, 1934, **24**, 72; *Hilgardia*, 1934, **8**, 149; *Calif. Agric. Expt. Sta., Bull.* 619, 1937 (San Joaquin Valley, California); *The Diagnosis and Improvement of Saline and Alkaline Soils*; R. E. McKenzie and J. L. Bolton, *Sci. Agric.*, 1947, **27**, 193 (Val Marie, Saskatchewan); R. Aladzem, *Bull. Un. Agric. Egypte*, 1947, **45**, 37; R. S. Snyder *et al.*, *Idaho Agric. Expt. Sta., Bull.* 233, 1940; W. L. Powers, *Oregon Agric. Expt. Sta., Bull.* 10, 1946.

[2] For a recent American bulletin on methods of doing this, see R. F. Reitemeier *et al.*, *U.S. Dept. Agric., Tech. Bull.* 937, 1948.

into the subsoil, improving the permeability of every layer into which it penetrates, for rarely does a drained soil have a permeability of less than a few inches of water a month.[1] Fig. 50, taken from some experiments of H. Greene on an impermeable Gezirah clay, in which sodium constitutes 10 per cent of the exchangeable ions, shows this effect of gypsum of increasing the permeability of the subsoil.[2] The land was flooded in April, and shortly afterwards soil samples were taken for moisture content. The soil was left fallow and then flooded

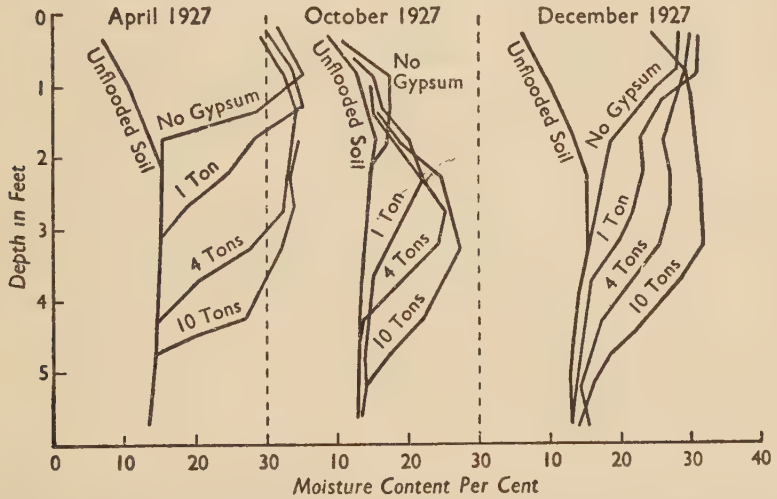


FIG. 50. Effect of gypsum on the permeability of soil. Percentage of moisture at different depths of unflooded soil (left-hand line) and of four flooded soils (right-hand lines) treated with different quantities of gypsum (tons per acre).

again in December and soil samples again taken. Without gypsum the water remained near the surface: with increasing dressings of gypsum it penetrated deeper and deeper into the soil. The drying out affected the first 2 feet equally whatever the gypsum treatment, but it did not equally affect the lower depths: the stores of water let down by the heavier dressings remained. The permeability of the soil can also sometimes be increased by very deep ploughing,[3] particularly if some gypsum is ploughed in at the same time or if gypsum is present in the subsoil. This is probably most efficacious if the subsoil has a compacted layer, for deep ploughing can bring this layer up to the surface, break it up to some extent, and expose it to the weather so its structure can be mellowed by drying and wetting in the hot season.

[1] W. L. Quayle (*Wyoming Agric. Expt. Sta., Bull.* 243, 1941) quotes examples of the value of flooding some Wyoming soils for two months before a crop is taken.

[2] *J. Agri. Sci.*, 1928, **18**, 531. See also with O. W. Snow, *J. Agric. Sci.*, 1939, **29**, 1.

[3] V. A. Kovda, *Khim. Sotsial. Zemled.*, 1941, No. 4, 31; I. N. Antipov-Karataev and A. A. Zaitzev, *Dokuchaev Inst. Soils*, 1946, Anth. 14.

The second operation is to establish a crop on the land, either sown or of natural weeds, for the plant roots will continue the task of increasing the permeability of the subsoil, both by abstracting water from it, so causing cracks to develop which will let water down quickly, and also by respiring carbon dioxide there which will reduce the alkalinity somewhat. The choice of crop is, however, limited, for it must be able to withstand the prolonged water-logging necessary for washing down as much sodium as possible into the deeper subsoil. Rice is an ideal crop, if other conditions are suitable, as it is kept water-logged throughout much of the season. Sweet clover and strawberry clovers are also suitable, so are many grasses and under some conditions so is lucerne, though lucerne will not stand water-logging so well as the others. Once these crops are established, they are encouraged to root deeply by being given heavy irrigations at as long intervals as possible, so the roots take as much water as they can from the subsoil before the next irrigation, though they must not be allowed to dry the soil so much that the soil solution becomes sufficiently concentrated to harm the roots. The first crop to be taken is often ploughed in as green manure, as the plant may contain too much salt for high feeding quality, and the green manure will not only produce carbon dioxide in the soil during its decomposition, but will also slowly set free plant nutrients such as phosphate, iron, manganese and zinc, which are very unavailable in alkaline soils.

Impermeable alkali soils can, therefore, be reclaimed and brought back into cultivation, though at the cost of much water, provided a water supply of good enough quality is available, for it must have a fairly low salt content because initially much of the water will have to evaporate from the soil surface, and the salt content must not build up enough to harm the crop.

A good crop rotation is an excellent insurance against alkali trouble, for grass, clover and lucerne leys can all build up the structure of a soil and improve its stability, and if these leys are consumed on the farm by dairy cattle, they will be returned to the land as farmyard manure, which again has a valuable action in maintaining the permeability of the surface soil.

Reclamation of Soils Damaged by Sea-water

Some interesting observations on the formation of a sodium clay by flooding with sea-water were made by T. S. Dymond in 1897–9.[1] The first effect of the flooding was to kill the vegetation by direct action of

[1] T. S. Dymond and F. Hughes, *Report on Injury to Agricultural Land on the Coast of Essex by the Inundation of Sea Water on 29th November*, 1897, Chelmsford, 1899.

the salt. But when the flood subsided and the rain-water began to wash away the salt, an interesting sequence of events was observed. The soil was at first "in remarkably good condition, ploughing well and forming a capital seed-bed". But with further removal of the salt "this condition gradually altered until the soil became difficult to work and in dry weather hard and cindery". The clay became more deflocculated, and would remain suspended for weeks in water while that from the unflooded land settled in a few hours.[1]

Dymond proved that the effect of the salt was to displace calcium and magnesium from the clay, and he argued that sodium had taken their place. He attributed the initial favourable physical conditions to the flocculation brought about by the small quantity of salt still left; when this was gone the clay became highly deflocculated.

TABLE 130

Influence of the Proportion of Divalent to Monovalent Bases on the Physical Conditions of Some Dutch Soils

Physical state	100 parts of replaceable bases contain:					
	Ca	Mg	Sum of divalent	K	Na	Sum of monovalent
Good, normal clay	79·0	13·0	92·0	2·0	6·0	8·0
Fairly good	65·8	17·6	83·4	4·0	12·6	16·6
Bad	42·1	25·0	67·1	6·5	26·4	32·9

The Dutch have had much experience in the last thirty years in reclaiming land from the sea, and their observations are in full accord with Dymond's. The soil starts very wet and sticky, but after a drainage system has been installed and some of the salt has been washed out, the surface soil acquires an excellent tilth. At this stage crops such as barley and mangolds will grow and yield well, and, in fact, the soil may have a high content of nitrate. It is in the following years, when the rain has removed still more salt so the clay becomes deflocculated, that troubles arise. The soils, however, usually contain enough calcium carbonate for calcium slowly to replace sodium. Once this has started, the soils can again be cultivated with care, though initially all

[1] An interesting example occurred later at E. Halton, in North Lincs. The land was formerly very productive, being especially suited for wheat and beans; it was flooded by the sea in 1921 and became infertile. It has not since been flooded, but it remains very sticky when wet and hard as concrete when dry, so that cultivation is impossible; even wild plants make but little growth (H. J. Page and W. Williams, *J. Agric. Sci.*, 1926, **16**, 551–73). In 1931 it still showed signs of deterioration, but the wild white clover sown in the grass mixtures had done well. It appeared, however, that the under-drains were choked with deflocculated particles.

cultivations must be very shallow so that the poor structural soil remains below.[1]

Table 130, taken from some of Hissink's work, shows how the proportion of exchangeable bases in the soil alters, starting off with the clay in very bad structure just after the salts have been washed out and finishing with the clay in good normal structure.

The Dutch, however, hastened this process when they set out to reclaim the land inundated with sea-water during 1944–45. Instead of waiting for the calcium carbonate to effect a replacement of the exchangeable sodium with calcium, which is slow because the sodium bicarbonate produced is alkaline and hence tends to keep the soil deflocculated, they added gypsum before the salt had been sufficiently washed out for the permeability of the soil to have been affected. This is much more soluble than the carbonate, and the sodium washes out as the neutral sulphate, hence has no tendency to reduce the permeability of the soil. By this means the soil can be kept permeable and cropped during the whole process of the replacement of sodium by calcium. The dressing of gypsum needed depends on the clay content of the soil, but it varies from 1 to 5 tons per acre.

[1] For a detailed account of this work, see D. J. Hissink, *Rapporten met betrekking tot de bodemgesteldheid van de Wieringermeer en van den Andijker Proefpolder*, 1929, No. 1, pp. 81–288; *Brit. Ass. Repts.*, 1931, p. 512; and several papers in *Trans. 6th Comm. Int. Soc. Soil Sci.*, Groningen, 1932, A, and 1933, B.

CHAPTER XXXIV

THE GENERAL PRINCIPLES OF SOIL MANAGEMENT

A GOOD SYSTEM of agriculture is required to produce as much food, either human or farm stock, as possible from the land at a reasonable cost without impairing its fertility. A farmer should always aim to leave the land in at least as productive a condition as when he acquired it. A good system of management must therefore ensure that the nutrient status of the soil is maintained; that all factors directly harmful to plant growth, such as high acidity, high alkalinity, or poor drainage are absent; that the land only grows the crops desired and not unwanted ones, that is, that weeds are kept under control; and that the soil particles themselves remain in place and are neither washed nor blown away.

The nutrient status of the soil is now very largely under the direct control of the farmer. If high-priced cash crops are being grown he can, if need be, buy all the plant food needed by the crop. But he should also aim at returning to the land all crop and animal residues that he can so as to minimise the loss of nutrients. Some soils, such as many semi-arid and desert, are naturally well provided with plant food; others, such as some tropical soils being derived from young, basic igneous rocks, are having their supplies of plant nutrients supplied by the weathering of the rock particles in the soil fast enough to meet the demands of the crops. Still others need to have nutrients added if they are to maintain good yields, and of these nutrients nitrogen and phosphate compounds are far the most important—nitrogen compounds wherever the water supply is sufficient to keep the plant growing all through its season, and phosphates in most parts of the world. These nutrients do not necessarily have to be added as fertilisers. The available nitrogen compounds in the soil can be greatly increased either by growing leguminous crops which contain nodules capable of fixing large quantities of atmospheric nitrogen, or by growing crops which return much nitrogen-poor organic matter to the soils under conditions in which decomposition can proceed rapidly and in which free-living nitrogen-fixing bacteria can flourish. The supply of other nutrients can also sometimes be increased by selecting crops which have a considerable power of extracting the nutrients in short supply from the soil minerals, or which have a particularly deep root system, and which can, therefore, concentrate the available soil supplies. In

all these cases, however, if the crop is not ploughed in, it should be fed to animals and their dung and urine put back on the land in a way that gives the smallest possible losses.

The prevention of harmful factors, such as acidity and alkalinity, have already been dealt with, and both require that the calcium status of the soil shall remain satisfactory. Good drainage is also essential to allow the crops to root deeply, hence be able to withstand drought and possibly frost as well, and to prevent the accumulation of harmful substances produced biologically whenever the oxygen tension in the soil falls too low. The soil must also be kept permeable, so water can drain through it at a reasonable rate, and the carbon dioxide content of the air around the roots not rise too high, nor the oxygen content fall too low. To some extent these factors can be controlled by proper cultivations, a subject that will be discussed in a later section.

The Principles underlying the Control of Soil Erosion

Soil particles can move by three processes: they may be blown away, they may be washed away, or the whole soil may slide or slump down a hill-side. Soil erosion can cause great troubles over large areas: dust storms, once started, may travel great distances; and conditions conducive to water erosion can lead to extensive flooding of valleys after storms, to silting-up of rivers, valleys and reservoirs, and to the great impoverishment of the land above the valley floor. Soil erosion is nearly always caused by an unsuitable method of agriculture being practised, and since among primitive peoples the system of agriculture affects their whole system life, methods of control involve not merely devising a system of agriculture which is better suited to the area and more productive, which is relatively easy, but also of altering the whole social outlook and sometimes even some of the religious beliefs or practices of the community, which is always an extremely difficult problem in sociology.

WIND EROSION AND SOIL DRIFTING

High winds can blow much material out of some bare soils, so that the wind itself becomes a dust storm, and soil material drifts across the land, forming dunes, filling up hollows and drifting against farm buildings and hedges. The physics of this action is now fairly well understood, as the principles have been clearly stated by R. A. Bagnold[1] and filled in in considerable detail for the particular case of soils by W. S. Chepil and R. A. Milne[2] at Swift Current, Saskatchewan.

[1] For a summary of his work, see his book *The Physics of Blown Sand and Desert Dunes*, London, 1941.

[2] *Sci. Agric.*, 1939, **19**, 249; 1941, **21**, 479; 1942, **23**, 154; *Soil Sci.*, 1941, **52**, 417; 1945, **60**, 305, 397, 475; 1946, **61**, 167, 257, 331.

Winds move soil and sand particles by three distinct processes: the finer particles are carried in suspension and may be transported as fine dust over very great distances; the coarser particles are rolled along the surface of the soil; and the medium-sized particles move by saltation. Bagnold has shown that saltation is, in fact, the primary process responsible for soil movement. The process of saltation is as follows. A strong eddy of wind at the soil surface picks up a sand grain and carries it up a few centimetres in the air where the wind has a much stronger horizontal component than at the soil surface itself. This wind then gives the sand grain a horizontal acceleration, and as the eddy which picked it up becomes dissipated, the sand grain falls back to the ground after having acquired considerable momentum. On impact it may cause some other sand grains to be shot a little way up in the air, and these in turn acquire momentum from the wind, and on hitting the ground may throw up other grains. Thus, the dust storm is due to this stream of sand particles which throw up others as they hit the ground. Soil movement by saltation thus requires a source of sand grains of a suitable size and a clear length of run for the wind to build up a sufficient density of sand grains moving in this way.

The size of particles taking part in saltation movement usually lies between 0·5 and 0·05 mm., with the grains in the size 0·1 to 0·2 mm. particularly active; and they need not be sand grains, but can equally well be soil aggregates or granules. Typically, the bulk of the grains do not rise more than an inch or so above soil-level, but a few rise to 3 to 6 feet; they rise steeply to their maximum height and then come down at an angle of between 10° and 16° with the horizontal. Typical paths for these grains are shown in Fig. 51, taken from R. A. Bagnold's *Blown Sand and Desert Dunes*. Grains smaller than about 0·1 to 0·05 mm., depending rather on the wind speed, do not take part in saltation, as they are sufficiently fine to be carried as dust in the turbulent motion of the wind, whilst grains larger than about 0·5 mm. are too heavy to be bounced into the air. Saltation thus brings the finer particles into the air and by bombarding the coarser particles rolls them along the surface of the soil.

The effects of soil blowing in the field are as follows. Soils containing a high proportion, that is, over 60 per cent of unaggregated sand grains and individual granules in the size range 0·1 to 0·5 mm., are very liable to blow, whilst those with less than 40 per cent do not usually blow easily. Such blowing soils are either fine sands, calcareous clays (for the calcium carbonate tends to give soil granules of this size) or fen soils containing well-rotted humus. The wind needs a run of from 50 to 500 yards to build up a large body of moving soil grains.

At the windward end of the area the particles finer than 0·5 mm. tend to accumulate; the sand dunes and drifts, which move mainly by saltation, are enriched in particles between 0·5 and 0·1 mm., and particles finer than 0·1 mm. are blown out of the area. The coarser of these particles, in the range 0·07 to 0·01 mm., are deposited on the outer fringes of the area as a loess.[1] Hence, the residual soils tend to become more sandy by this process. As one travels with the wind the grains fill up all hollows, and if there are no obstructions leave an

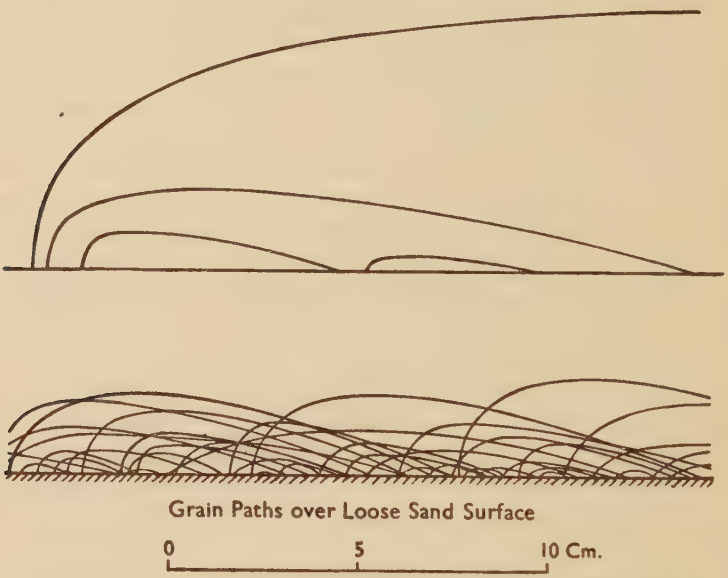


Fig. 51. *Upper*: Typical paths of sand grains moving by saltation. *Lower*: Paths of sand grains moving over a loose soil surface.

almost level surface having shallow ripples across it. This smooth surface becomes resistant to further erosion as soon as the supply of incoming sand grains ceases. These effects are shown up most clearly in fine, sandy soils having few granules.

The effects are rather different for granulated clays, because the movement of different-sized granules does not necessarily involve any differential movement of the actual mineral soil particles. Further, the granules have not the abrasive action of sand grains, so typically they produce less dust to be blown out of the area, though they drift just as badly.

The primary areas suffering from dust storms are on the edges of the desert, for blowing is only possible with dry soils. The desert and

[1] F. E. Zeuner, *The Pleistocene Period*, Ray Soc. London, 1945.

the fringes of the desert give this dryness and are also regions liable to strong winds. Because of the dryness, it is often difficult to keep vegetation growing on the soil during periods of droughts, so the soil is liable to have many bare patches, and it is in the bare patches that centres of blowing start. The primary problems of erosion control are only concerned with bare or partially bare soil, for soil well covered with vegetation never blows. Further, the type of agriculture practised in these semi-arid regions is either wheat growing with the necessary fallows for storing water, or ranching. In the former type there is always some land not in crop, and in a series of dry years most of the land will carry no crop. This is what happened in the wheat belt, or dust bowl, of America during the run of drought years in the mid-1930's. In the ranching type, a spell of dry years almost of necessity involves serious over-grazing of the range, and may again result in large areas being left almost bare.

The principle of all methods for controlling wind-blowing is to prevent saltation building up a sufficiently high density of moving sand grains. This can be done either by trapping the moving grains before they have become dense, or by reducing the velocity of the wind over the surface sufficiently to prevent it being able to pick up sand grains, or by covering the soil with a non-erodible surface so that most of the sand grains moving by saltation lose their momentum to this surface rather than to other sand grains in the saltation range.

Methods have been devised for reducing the liability of cultivated soils in the dry farming regions from blowing.[1] In the first place, no continuous large area of land is left fallow, but the fallow alternates as strips with the sown, the strips running across the direction of the prevalent high winds. An example of this from Alberta is illustrated in Plate XXXII. Fallow strips 100 to 200 yards wide, alternating with sown strips of the same width, normally blow very little, unless the soil is very erosive, for the wind cannot produce enough sand particles moving by saltation either to raise much dust or to cause much drifting before they are caught by the crop. However, this method by itself is only of limited value with soils very liable to blow, and at times of the year before the sown crop has germinated or grown large enough to prevent saltation. A modification of this method can be used in areas of adequate rainfall to protect areas of land liable to blow before the sown crop has grown enough to give protection. Comparatively narrow strips of permanent grass, if the herbage is 1 to 2 feet high, will stop saltation by entrapping the sand provided it is wide enough for the entrapped sand to be well away from its leeward side.

[1] For accounts of these methods, see E. S. Hopkins *et al.*, *Canada Dept. Agric., Publ.* 568, 4th revision, 1946; A. E. Palmer, *Emp. J. Expt. Agric.*, 1945, **13**, 125; *U.S. Dept. Agric., Farmers' Bull.* 1771, 1937; 1833, 1939; 1864, 1941.

This method, however, is only efficacious in areas where the rainfall is adequate to ensure a good crop of grass every year. In extreme cases the grass strip can be replaced by a narrow but thick hedge.

The second method of control, which is used in conjunction with strip cropping, is to reduce the velocity of the wind at the soil surface as much as possible, and do anything else that reduces the chance of the wind picking up any sand grains. Winds can be moderated by planting shelter belts, but the climate is often too dry and other conditions unfavourable for most trees to grow quickly,[1] and the effect of the shelter belt is small, limited to not more than five times its height on the windward or twenty to thirty times its height on the leeward side.[2] This method, however, is useful in the isolated areas of eastern England and Sweden,[3] for example, where soil-blowing can be serious.

W. S. Chepil[4] has given an example from Kaifeng in Honan Province, China, where this method is practised to stabilise a sandy soil. Single belts of willow, which grow to about 12 feet high, are planted in strips 50 to 60 feet apart across the direction of the prevailing wind and in strips 100 to 500 feet apart at right angles to this direction, leaving only small rectangular strips of field for cultivation.

Suitable cultivation methods can also reduce the chance of the wind picking up a sand grain. Obviously, if the soil structure can be made cloddy there will be no unaggregated sand particles of a suitable size to be picked up. Cultivating the soil when moist and never pulverising it helps, but it is not always possible to restrict cultivations to these times. Laying the soil down to drought-resistant grasses whose roots bind the soil together also improves the structure. Laying the soil up in ridges also reduces erosion through it preventing the build-up of particles moving by saltation.[5] It is also particularly important that any knoll or dune built out of erodible sand or soil particles should be very well stabilised, otherwise it will serve as a good source for particles to begin to drift by saltation at quite low wind speeds.

Another method, that has been used in parts of the Canadian prairies since 1915, is stubble mulch cultivation, described more fully on p. 580, in which the previous year's stubble is left anchored in the surface, and during the fallow period all cultivations are done below or on the surface in such a way that the previous year's stubble remains anchored in the surface but sticking out above it, as is shown in Plate XXXIII. Thus, weeds can be kept in control without the soil surface

[1] For an account of shelter belts, see, for example, *U.S. Dept. Agric., Farmers' Bull.* 1405, 1936; J. S. Yeates, *Farm Trees and Hedges, Massey Agric. Coll. (New Zealand) Bull.* 12, 1942.
[2] See, for example, J. W. Toumey, *Foundations of Silviculture*, New York, 1928; W. Nägeli, *Mitt. Schweiz. Anst. Forstl. Versuchsw.*, 1943, **23**, 223.
[3] G. Petersson, *LantbrHögsk. JordbrFörsöksanst. Medd.*, 1947, No. 20.
[4] *Agron. J.*, 1949, **41**, 127. [5] W. S. Chepil and R. A. Milne, *Soil Sci.*, 1941, **52**, 417.

being left bare. Typically, in the wheat-growing areas where these methods were first developed, the wheat is harvested with the combine, a long stubble is left and the straw coming from the combine is also left on the ground. Thus, the wind velocity at ground-level is always very low because of the resistance of the stubble and straw, and the straw and stubble together reduce the chance of a moving sand grain throwing up others by saltation. Chepil[1] found, in fact, that as little as $\frac{1}{4}$ ton per acre of straw had an appreciable effect in reducing soil drifting. Stubble mulch farming may introduce some difficult problems in insect control, particularly the wheat stem sawfly and insects of the grasshopper-locust type, because they may be able to over-winter on the stubble, but so far few troubles of this type have arisen.[2]

All these methods used together as far as possible give good control of wind-blowing in most years, but it must be borne in mind that there are no methods of control yet available on cultivated land during periods of drought extending over several years. These lands cannot be sown down to grass or to anything else once the drought has started, though if one could forecast the onset of prolonged drought a year or so ahead they could be grassed down and left ungrazed over the dry period, and this might be enough to prevent the disastrous dust storms of the mid-1930's recurring.

EROSION BY RUNNING WATER

Water running over the surface of the soil is a far more serious cause of erosion in most parts of the world than is the wind. Water only runs off the soil surface when the rate of rainfall exceeds the rate of infiltration of the water into the soil, hence every factor that reduces the permeability of the soil increases the likelihood of water run-off. This run-off water has two consequences of great importance: the more the run-off the greater is the "flash" flood in the rivers draining the area after storms, and the greater is the amount of silt and soil the water is likely to pick up and hence the more silt will be deposited by the river after the floods have subsided. Hence, this type of run-off and erosion gives very difficult problems of flood control on the one hand and silt control on the other. As examples of silt trouble can be mentioned the burying of crops under silt in the flood plains of rivers, the rapid silting up of reservoirs, and the difficulty of keeping irrigation channels clear and irrigated fields level if the river supplying the irrigation scheme is silty.

Run-off can have a third consequence of very great importance, for the rain-water, instead of sinking into the soil, runs off the land and

[1] *Sci. Agric.*, 1944, **24**, 307.

[2] For an example of trouble of this type, see D. A. Wilbur *et al.*, *J. Amer. Soc. Agron.*, 1942, **34**, 16.

hence cannot be used by the vegetation. Run-off therefore increases the liability of the crop to damage by drought, and this effect is particularly serious in semi-arid regions and in all those parts of the tropics with a short, or uncertain rainy season, for even in these regions the rains that fall tend to fall in heavy storms of short duration.

The typical cause of serious erosion is that an unsuitable method of farming is being practised. Well-managed forests and pastures are almost immune from erosion troubles, whilst any system of agriculture that involves having large bare areas of soil during heavy rain storms are very susceptible. Thus, in many semi-arid parts of the world, liable to long drought and heavy storms and in which ranching is the natural method of land use, over-grazing in the dry season leaves the soil unprotected against the rain storms when they come, and hence very liable to serious soil erosion.[1] Over-grazed ranges are not only more liable to erosion but also may be more favourable habitats for rabbits and other rodents which themselves graze the range,[2] and hence will be an added cause for its decreased productivity. It is under just such conditions of limited water supply that water run-off is such a serious matter, because it causes the whole area to suffer unnecessary drought, and this is often a much more important factor than soil loss in semi-arid areas.

The erosive power of water, running over the surface of the soil, depends on its power of bringing soil into suspension and of carrying the soil load so brought in. These powers increase very rapidly with the velocity of flow and to some extent with the thickness of the water sheet.[3] Hence, the two fundamental principles in all methods of combating or reducing soil erosion by water are the maintenance of the permeability of the soil, to reduce the amount of run-off as much as possible, and ensuring that what run-off occurs takes place as thin sheets of slowly moving water. This latter point is difficult to achieve, for water running off a slope always tends to form runnels, in which the flowing water is concentrated and hence its power of erosion increased; and these runnels collect as fast flowing flood streams which may soon begin to cut deep gullies. Hence, the need to keep the length of run of the water over the bare soil down to a reasonable length, for the longer the run the more the chance of runnelling. Thus, at Zanesville, Ohio, the amount of soil washed off runs of 36, 76 and 145 feet of soil continuously under maize having a 12° slope

[1] For examples, see H. Glover, *Erosion in the Punjab*, Lahore, 1944; K. B. Cumberland, *Soil Erosion in New Zealand*, Wellington, 1944; J. M. Holmes, *Soil Erosion in Australia and New Zealand*, Sydney, 1946.

[2] V. T. Vochies and W. P. Taylor, *Arizona Agric. Expt. Sta., Tech. Bull.* 86, 1940; E. H. Graham, *The Natural Principles of Land Use*, New York, 1944; *J. Soil Water Conserv.*, 1946, **1**, 55; R. L. Piemeisel, *U.S. Dept. Agric., Tech. Bull.* 654, 1938.

[3] For some experiments showing this, see J. F. Lutz and B. D. Hargrove, *North Carolina Agric. Expt. Sta., Tech. Bull.* 78, 1944.

were 83, 99 and 117 tons per acre per year, yet the actual amount of water running off these three areas was the same.[1]

The effect of erosion on the particle size distribution of the soil left behind and the soil carried away depends on the velocity of the water running off the land. High velocities of run-off carry away all the soil particles, even stones, but at moderate velocities, when erosion is not very serious, the silt and clay particles tend to be removed and the sand particles to remain behind. Hence, land suffering from moderate erosion tends to become sandier, and the deposits left behind by the run-off water in the valleys more silty than the original soil.[2]

Various methods are employed to slow up the water and keep it flowing in as uniform a sheet as possible over the soil, of which strip cropping on the contour and the use of terraces are typical. In strip cropping, strips of land well covered with vegetation and hence resistant to erosion alternate with strips less well covered and hence more susceptible, whilst the terraces are banks of soil, often up to 18 inches high, running either on the contour or having a gentle fall, which intercept the water running off the land above them. The water either ponds up behind them if they are run on the contour, or runs off into well-protected waterways if they have a gentle fall. Hence, the base of the terrace must be able to withstand a stream of water running along it, so it is often necessary to grow a close-spaced crop, or a grass ley in it for this reason. Terraces can also be much lower structures, even only an upturned furrow, if they are run at frequent intervals on the contour across a grazing range. This slows up the water at regular intervals, and if the top of these small terraces are on the level, water cannot collect in streams, but spreads out uniformly each time it reaches one. The design of terrace systems and the proper width of close-growing crops with wide-spaced ones in strip cropping are problems that lie outside the scope of this book.[3]

The maintenance of soil permeability can be extremely difficult, because the main cause of erosion is heavy rain storms. Thus, at Tyler, Texas, land under cotton lost on the average 21 tons of soil a year, but of this loss 12·5 tons were lost, on the average, in the two days in which the two heaviest storms occurred.[4] There are two reasons for this; one is that the heavy storm puts much water on the land very quickly, so unless the soil is very permeable a high proportion has to

[1] *U.S. Dept. Agric., Tech. Bull.* 888, 1945.

[2] For some examples of this, see L. A. Forrest and J. F. Lutz, *Proc. Soil Sci. Soc. Amer.*, 1945, **9**, 17.

[3] For detailed experimental results on different types of soils for different crops on which practical recommendations must be based, see the reports of the American Soil Erosion Research Stations, *U.S. Dept. Agric., Tech. Bulls.* 837, 1945; 859, 860, 873, 1944; 883, 888, 1945; 916, 1946; 959, 1948; and for details of the methods advised, H. H. Bennett, *Soil Conservation*, New York, 1939.

[4] *U.S. Dept. Agric., Tech. Bull.* 916, 1946.

run off; but the second reason is that heavy storms fall as large, and hence fast-falling raindrops, which have a high momentum and kinetic energy when they hit the ground. M. L. Nichols and R. B. Gray[1] have calculated that 2 inches of heavy rain in which the drops fall at 20 miles per hour have to dissipate 6,000,000 foot-pounds of work per acre on hitting the ground—enough to raise the top 6 inches of soil 3 feet in the air if it all fell at once. Hence, the impact of the raindrops on a soil surface is to smash up all clods on the surface, and leave it level.[2] But in the process fine sand, silt and clay granules have become dispersed in the water, so the rain-water becomes muddy on hitting the ground.

It has already been stressed that the infiltration of water into a soil, and its drainage through the soil, takes place in the wider pores, typically those between soil clods and crumbs, and down root and worm holes and other such discontinuities. The effect of a heavy rain on a bare soil is, therefore, to seal up the openings of these channels at the surface, both by soil from the disintegrated clods being knocked into them and by silt carried by the water settling out in them as the water percolates slowly down. Hence, shortly after the beginning of a heavy storm a bare soil surface will have become virtually impermeable to water, even though just below it there are channels running through into dry soil. The only ways the surface layer can be kept permeable in such conditions are to prevent the rain actually hitting the soil clods, for it is not possible to give the soil a crumb structure strong enough to withstand such impacts.

The soil surface can be protected from the raindrops either by growing a close-growing crop on it, so the leaves of the crop take the impact, or else by covering it with a straw, farmyard manure or leaf litter mulch. This again ensures that only clean, slowly moving water comes in contact with the surface of the soil, and hence causes a minimum reduction in the surface permeability. Even stubble left anchored in the soil, or the straw from the combine left on the soil,[3] as is done in stubble mulch cultivations, help considerably to maintain the permeability of the soil surface by taking much of the impact of the falling raindrops.

Ensuring that the water just after reaching the soil remains clear is, however, only part of the problem. It must remain as clear as possible as it runs over the surface, so impairing the permeability of the surface soil as little as possible. It is at this stage that a stable soil structure,

[1] *Agric. Engng.*, 1941, **22**, 341.

[2] For examples and photographs, see J. O. Laws, *Agric. Engng.*, 1940, **21**, 431; W. D. Ellison, ibid., 1944, **25**, 131, 181, and 1947, **28**, 5 papers.

[3] For some details of the effectiveness of these methods, see F. L. Duley and L. L. Kelley, *U.S. Dept. Agric., Circ.* 608, 1941; J. C. Russel, *Proc. Soil Sci. Soc. Amer.*, 1943, **7**, 77.

obtained by proper use of farmyard manure, or grass or legume leys, can be so valuable. But even a good stable structure has only a limited effect on the clearness of the water, and close-growing crops, such as leys which cover the soil, or wheat drilled along the contour, or stubble anchored to the soil, or a surface mulch all help by slowing up the flow of the water, hence reducing its power to carry silt or soil. And it is for this reason that close-growing crops grown on the contour as strips between areas of wide-spaced crops, are such a valuable method of controlling soil and water losses, provided the slope of the land is not too steep and no gullying has begun.

The effect of various cropping practices on the amount of water and soil lost from strips of different crops has been measured in many experiments in America. An example from Zanesville, Ohio, will illustrate these points. Plots were laid out up a 12° slope on a silt loam soil. Over a nine-year period the average annual rainfall was 38 inches, and half the soil losses were caused by thirty-three rains during this period. The plots were cropped either to continuous maize, or to a four-year rotation of maize-wheat-two-year ley, or to permanent pasture, and the mean annual soil and water losses were:

	Average run-off of water		Soil loss, tons per acre
	Inches	As per cent of rainfall	
Continuous maize	15	40·3	99·3
Crops in rotation:			
Maize	9	23·7	41·5
Wheat	9	24·8	11·4
First year ley	7	17·7	0·6
Second year ley	5	12·8	0·2
Permanent pasture	1·6	4·3	0·02

These results show it is easier to reduce soil loss than water run-off by proper choice of crops, and that the better soil structure under maize following the two-year ley reduces both the soil and water loss very considerably compared with the soil with a poorer structure under continuous maize.

Strip cropping, like stubble mulch farming, may bring some difficult problems of insect control in its train, for it allows some of the plant-eating insects of the grasshopper-locust type to over-winter on the grass or cereal strips, so giving them the possibility of breeding quicker in the spring and so becoming a plague more easily. But the strips also allow the insects predaceous on these leaf-eaters to increase in numbers, and up to the present time the net effect of these covered strips on the plant-eating insects has been small.

CHAPTER XXXV

PRINCIPLES OF THE METHODS OF SOIL CULTIVATION

THE GREAT CHANGES in technology that have taken place in the world during the last few centuries originated in north-west Europe, and this has been very apparent until a few decades ago in the improved methods of soil cultivation that were being practised by men of north-west European stock over the whole world. But though these methods have been very successful in temperate regions, they often had disastrous consequences in other areas. Thus, cultivations based on the mouldboard plough and weed-free soils are not universally appropriate. Unfortunately, at the present time there is still much controversy, particularly among successful farmers, about the consequences and necessities of different practices, and the account to be given here would be disputed by some of them.

There seems no question that the agriculture of north-west Europe has been centred on the mouldboard plough, an implement which when well used cuts and inverts a furrow and leaves the land completely bare of all vegetation. Mouldboard ploughing, therefore, buries all surface rubbish, and can be made to bury manure put on the surface, and in consequence can distribute relatively immobile fertilisers, such as phosphates, potash and lime, throughout the depth of ploughing; and it also loosens the layer of soil ploughed. The shallowest depth to which the surface of the soil is buried and the amount of comminution or aggregation of the soil clods depends on the shape of the mouldboard.

The ability of the mouldboard plough to kill weeds and prevent weed seeds germinating is undoubted, and under cool, humid conditions, such as the typical English late autumn to early spring, there appears to be no other implement that has anything like the ability to prevent weeds growing in the seed-bed; and the deeper the plough is set the more efficiently it prevents surface weeds from germinating and allows deep-rooting perennial weeds to be controlled by bringing up more of their root system to the surface.

The importance of distributing manure and fertilisers through a greater depth of soil than can be done merely by working them into the first few inches of surface soil is still under investigation. Obviously, if one is reclaiming land with a very acid subsoil, one will improve the drought resistance of a crop growing on it by spreading lime on the

surface before ploughing, then ploughing as deeply as possible, and then spreading another dressing of lime on the surface; for this will neutralise the subsoil acidity more rapidly and allow the crop to become deeper rooting. But on soils in which roots can penetrate several feet quite easily, such as most agricultural soils, the occasions on which it is desirable to incorporate the manures and fertilisers deeply have not been well established, though general experience and general theory indicate that it should be in moderately dry years. For, as pointed out on p. 423, plant roots cannot extract nutrients from a dry soil, and tend to dry the soil from the surface downwards, hence the deeper the nutrients are incorporated, the longer after the onset of the drought will some of them remain in moist soil. It is probably for this reason that the practice of drilling part of the potash and phosphate, or in some conditions a complete fertiliser, on the bottom of an 8- to 10-inch deep plough furrow[1] has been spreading in regions subject to short but severe summer droughts.

The importance of the depth to which the soil is loosened has not been established yet. There are many progressive farmers in parts of Great Britain who are ardent advocates of deep ploughing, and it is not yet known just what benefits they derive from ploughing 12 to 18 inches deep. This deep ploughing naturally increases the permeability of the ploughed soil and the goodness of its aeration, and hence allows the soil to drain quicker provided the deeper subsoil is permeable or has an efficient drainage system; though if the drainage of the deeper subsoil is very impeded, deep ploughing merely increases the volume of the large pores that can become water-logged in wet weather, and hence helps to turn the land into a marsh. Subsoiling, that is, loosening the subsoil without bringing it to the surface, also improves permeability, and the point at issue between deep ploughing and subsoiling is the relative length of time that the improved permeability lasts. This improvement would be expected to be most beneficial on soils having a comparatively thin pan under the normal depth of ploughing, such as that produced by long-continued ploughing to a constant depth or by a tractor wheel running on the bottom of the furrow, and would most likely be seen on heavy soils.

There is, however, a very extensive body of experience and of experimental results that have shown deep ploughing to have no beneficial effects on the crop, and that, for as far as crop yields are concerned, ploughing depths of 4 inches appear to be quite satisfactory, though this is probably only true if the land is already free from weeds. Certainly, most of the Rothamsted experiments[2] have shown that

[1] For the results of many American experiments on the value of these practices, see the *Proceedings of the National Joint Committee of Fertiliser Application.*

[2] E. W. Russell and B. A. Keen, *J. Agric. Sci.*, 1941, **31**, 326.

4-inch ploughing, or indeed any method of loosening the soil to a 4-inch depth, was all that wheat, barley and mangolds needed, provided the land is clean, though the Rothamsted experience has been, as already stated, that deeper ploughing eased the task of keeping the land clean very considerably. The former part of this result has also been found by Swedish[1] and many American workers.[2]

The great limitation of the mouldboard plough is that, by leaving the soil surface completely bare, it leaves it in a condition very susceptible to erosion, and if the primary objective in mouldboard ploughing is to control weeds, particularly in the seed-bed and the early stages of the crop's growth, then the problem of replacing the mouldboard plough is that of finding alternative methods of weed control. The most likely line of development is to try and improve the methods developed six or more thousand years ago in the Middle East and Egypt, based on a plough that merely loosens the land without turning a furrow—a plough that is very like a cultivator tine. Such a plough will loosen the soil, will undercut all weeds and plants, but will leave them on the surface. Provided the weather is dry, particularly hot and dry, during or just after this operation, the surface weeds will be dried up and killed, but they will remain as a mulch anchored in the surface to help protect it against wind and rain. This is, in fact, the principle of stubble mulch farming being developed in the semi-arid parts of America. The methods being tried are to work the soil with wide sweeps attached to cultivator tines, such as is shown in Plate XXXIII or with rotary rod weeders, about 2 inches below the surface,[3] leaving all the dead weeds and last season's stubbles and crop residues lying on the surface, but anchored in it as is also shown in that Plate. The next crop is sown by cutting a narrow band through this mulch and putting the seed into the seed-bed prepared below it. But this method is only successful in regions where cutting weeds about 1 to 2 inches below the surface is sufficient to kill them, and this needs dry weather and the absence of weeds that cannot easily be killed by this method. Duley and Russel have given an example of this for maize in Nebraska. In dry years the maize yielded relatively much better under stubble mulch cultivation than ploughing, 31 compared with 17 bushels per acre, but in wet years relatively worse, 62 compared with 72; the full causes of this difference have not been recognised.

The correct implement to replace the mouldboard plough on

[1] G. Torstensson and G. Enge, *Kgl. LantbrAkad. Tidskr.*, 1943, **82**, 296.

[2] See, for example, C. E. Millar and A. G. Weidemann, *Michigan Agric. Expt. Sta. Quart. Bull.*, 1947, **30**, 5.

[3] For a description of the machinery being developed, see F. L. Duley and J. C. Russel, *Agric. Engng.*, 1942, **23**, 39; M. B. Cox, ibid., 1944, **25**, 175; *U.S. Dept. Agric., Farmers' Bull.* 1797, 1938; 1997, 1948.

erodable land in the humid tropics has not yet been developed. The native implement is the hand-hoe, and the area cultivated is divided into small, isolated patches. The methods being developed are taking advantage of the fact that in most tropical regions there is a wet and a dry season, and the object is to kill the weeds in the dry season, probably by some method such as the stubble mulch, and plant at the very beginning of the wet, so the land is covered with a crop as soon as possible.

A second series of cultivation operations that have been of great importance in the past, are the hoeings done between the rows of a wide-spaced crop, and it is probable that in England, at any rate, one of the principal reasons the seed drill was introduced was to allow the subsequent crop to be horse-hoed. These hoeings do two distinct things: they kill the weeds growing between the rows and they loosen the surface of the soil. At one time the agricultural scientists considered that the loose surface, the dust mulch as it is called, helped to reduce the amount of water lost by the soil, and though this is still believed by many farmers, field experiments all over the world have shown that this mulch does not normally have this effect.[1] The importance of this hoeing appears to lie in the weeds it kills and not in the loose tilth it creates,[2] and this is borne out by the practical experience that other methods of weed control that do not involve creating a soil mulch, such as using differential chemical weed killers and miniature flame throwers,[3] can benefit the crop as much as hoeing.

There are, however, a few isolated experiments in which loosening the surface soil has improved the yield of sugar-beet, possibly by improving the soil aeration,[4] but the particular circumstances needed for this unusual result to be found have not been established. As pointed out on p. 359, there is no reason to expect that a surface dust mulch could conserve much moisture, and the few experiments made on the moisture content of hoed and unhoed soils are in accord with this expectation. However, hoeing may increase the nitrate content in the surface soil, but the growing crop does not seem able to make any use of it.[5]

Surface hoeing may have, however, three undesirable consequences.

[1] H. C. Pereira (*Emp. J. Expt. Agric.*, 1941, **9**, 29) has collected together the results of several hundred experiments on this subject.

[2] For some recent experiments, see E. W. Russell *et al.*, *J. Agric. Sci.*, 1942, **32**, 330 (England); A. R. Saunders, *Farm. S. Africa*, 1944, **19**, 295; A. G. Weidemann, *Michigan Agric. Expt. Sta. Quart. Bull.*, 1947, **29**, 320; G. H. Burvill *et al.*, *J. Dept. Agric. W. Aust.*, 1943, **20**, 224.

[3] For the use of this technique, see F. E. Farwell, *Sugar*, 1945, **40**, No. 2, 35; H. T. Barr, *Louisiana Agric. Expt. Sta.*, *Bull.* 415, 1947.

[4] L. D. Baver and R. B. Farnsworth, *Proc. Soil Sci. Soc. Amer.*, 1941, **5**, 45; F. W. Smith and R. L. Cook, ibid., 1947, **11**, 402.

[5] H. C. Thompson, *Cornell Agric. Expt. Sta.*, *Mem.* 107, 1927, *Bull.* 521, 1931; G. C. Moore, ibid., *Bull.* 662, 1937; R. D. Sweet, ibid., *Bull.* 795, 1943.

The soil is left bare, the loose mulch is not stable enough to withstand a heavy storm, and the production of the loose mulch may involve harming the surface-feeding roots of the crop. This damage can be important in established crops of sugar-beet at Rothamsted,[1] and can be serious for shallow rooted plantation trees, such as tea and coffee.[2] The methods that must be adopted to control weed competition where these two consequences are really important will be discussed in the next section.

If the main effect of hoeing is to kill weeds, and its disturbing effect on the surface roots of the crop is undesirable, as with coffee, sugar-beet, and many market-garden crops,[3] hoeing should be done as shallow as possible and at a time when it either kills most weeds or any particular pernicious weed, or when the weeds have a particularly depressing effect on crop growth. There is an increasing body of evidence, which has not yet been properly summarised, which indicates that weeds are usually most harmful to the crop during the early, and particularly the very early, stages of growth. Hence, the importance of clean weed-free seed-beds, and of beginning hoeing as soon as practicable. However, if deep rooting perennial weeds are present, the best method of control may be to let them start growing and to wait until the food reserves in their root system are at a minimum before cutting down their aerial parts. J. C. Frazier[4] found that for bindweed in Kansas, this occurred about eight days after emergence, and that if the hoeing were delayed until this time, the weed was weakened much more than if the hoeing was done just after emergence.

There is also a close connection between the level of manuring, the amount of cultivations used and crop yield. Thus, E. W. Russell[5] found that on the Woburn light loam soil weed control was more important for sugar-beet growing under conditions of a low nitrogen supply than under a high one, as is shown in Table 131. Further, the high supply will often benefit the crop more than the weeds, so that it will grow faster than the weeds and smother them: it will, in fact, be its own weed controller.[6]

Part of this effect is due, however, to the weeds removing nitrogen from the soil the beet would otherwise use. This effect has been found in experiments on stubble mulch cultivation methods in regions of rather high rainfall, for the method did not control weeds well and

[1] E. W. Russell *et al.*, *J. Agric. Sci.*, 1942, **32**, 330.
[2] A. S. Thomas, *Emp. J. Expt. Agric.*, 1944, **12**, 191.
[3] R. D. Sweet, *Cornell Agric. Expt. Sta., Bull.* 795, 1943.
[4] *Trans. Kansas Acad. Sci.*, 1941, **44**, 164. See also A. L. Bakke *et al.*, *J. Agric. Res.*, 1944, **69**, 137.
[5] *Proc. Inst. Brit. Agric. Engnrs.*, 1945, **3**, 99.
[6] For other examples of nitrogen fertilisers having this beneficial effect, see H. R. Cooper, *Indian Tea Assoc., Mem.* 6, 1946 (for tea), and *Amer. Fert.*, 1947, **107**, No. 5, 12 (for maize).

TABLE 131

The Effect of Weeds and Sulphate of Ammonia on the Yield of Sugar-beet

Woburn, 1939–43. Sulphate of ammonia at 3–4 cwt. per acre

Yield in tons clean beet per acre

Crop	No sulphate of ammonia	With sulphate of ammonia	Response to nitrogen
Clean weeded	11·1	15·0	3·9
Weedy	8·8	14·6	5·8
Depression due to weeds . .	2·3	0·4	—

the crop, usually maize, responded better to nitrogen and sometimes potassium also than did that on clean ploughed land.[1]

However, this method of compensating for and controlling the harmful effects of weeds fails completely if the additional fertiliser benefits the weeds more than the crop. Thus, T. Eden[2] found that adding phosphate to tea on some soils increased the yield, but once a certain level of phosphate had been reached a weed that depressed the growth of tea began to respond better to the extra phosphate than did the tea. Hence, keeping the phosphate level in the soil under very careful control enabled the tea to get most of the phosphate it needed, whilst at the same time it prevented a weed that is difficult to eradicate from developing well.

This type of weed control is of particular importance for shallow rooting crops, such as tea and coffee, grown under conditions of high seasonal rainfall, for it is desirable to keep the soil between the bushes covered either with trash or vegetation, but the vegetation must not compete with the crop. Only recently has the importance of methods of weed control which obviate the necessity for cultivation been realised, so very few of such methods have yet been developed.

There is one common cultivation operation often done that is not connected with weed control, and that is rolling. This can be very valuable if the soil is rather dry, for by pressing the soil closer to the plant roots, or to the seed in the seed-bed, it also presses the water closer to the root or seed. Rolling, however, has a marked beneficial effect on some light soils and some thin soils over chalk. The benefit in the sands may be merely due to bringing the moisture closer to the

[1] G. M. Browning *et al.*, *Proc. Soil Sci. Soc. Amer.*, 1944, **8**, 424; 1945, **9**, 142; C. L. Englehorn, *N. Dakota Agric. Expt. Sta., Bull.* 341, 1946.

[2] *Emp. J. Expt. Agric.*, 1940, **8**, 269; *Tea Quart.*, 1947, **29**, 5; with T. E. T. Bond, *Emp. J. Expt. Agric.*, 1945, **13**, 141.

root, but this certainly is not the cause of the benefit on the chalk soils. English experience is that compaction of these soils is essential, and though the cause of this has not yet been proved, it is possible that a part at least is due to the slightly poorer aeration, and hence higher carbon dioxide content of the soil air that it brings about; for, as was explained on p. 101, this will help to reduce the *p*H of the soil around the plant roots from 8·4, at which the plants will suffer from malnutrition due to the unavailability of phosphates and some trace elements, to a lower value at which these nutrients become more readily available.

Mulches and Shade Trees

The practice of applying a layer of dead vegetable waste material, such as straw, hay or old grass, composts or farmyard manure, on to the surface of the soil around trees and bushes has been prevalent for a very long time in many parts of the world. These surface mulches can have very important effects on the conditions in the surface layers of the soil, and in consequence on the crops with shallow root systems. Thus, mulching has been widely used for many fruit trees and bushes and for tropical plantation crops with superficial root systems such as coffee and tea.

A surface mulch has two types of effect on the soil: a characteristic effect, due to it being on the surface of the soil, and a general effect, which it would equally well have if it were ploughed into the soil, due to the plant nutrients set free as it decomposes. The primary specific effects of the mulch are confined to the superficial soil layers, which it keeps both cooler and at a more even temperature, and damper and more permeable to water than the unmulched soil.

The effect on soil temperature is shown most strikingly in tropical countries which have a very large diurnal temperature change. Thus, S. M. Gilbert,[1] working with coffee in Tanganyika, found that the temperature of the soil at 2 inches depth might vary by 12° C. during the day, whilst under a mulch it varied by 2° to 3° C. Some results of T. M. McCalla and F. L. Duley,[2] in Lincoln, Nebraska, also illustrate this effect. The average daily maximum temperature from June to September in the top inch of soil under maize was 31·2° C. if the soil was clean weeded, and 23·6° C. under a mulch of 8 tons per acre of straw, whilst the average daily minimum temperatures were 17·9° C. and 19·7° C. respectively, giving mean temperatures of about 24·5° C. and 21·6° C. respectively, with an average daily range of 13·3° C. and 3·9° C. respectively. The mulched soil is much cooler during the heat of the day and rather warmer during the night. This effect of a mulch

[1] *E. Afric. Agric. J.*, 1945, **11**, 75. [2] *J. Amer. Soc. Agron.*, 1946, **38**, 75.

in reducing the maximum temperature in the soil, without greatly affecting its minimum temperature may also be shown by a dust mulch, that is, the loose surface layer of the soil produced by hoeing.[1]

The mulch slows down the rate of evaporation from a bare, wet soil very considerably for, as pointed out on p. 357, the rate of evaporation is controlled by the proportion of the energy absorbed by the soil which is used for evaporating water, and by the rate of removal of the water vapour from the region where it is being produced. So long as the wet soil is exposed to the air, the water vapour is rapidly removed by the general turbulence of the air, but if the water vapour must diffuse through a thin dry layer of soil, or through a mulch which keeps the air almost stationary, then the rate of diffusion limits the rate of evaporation, and this rate is about $\frac{1}{12}$ inch per week instead of $\frac{1}{8}$ to $\frac{1}{10}$ inch per day for normal hot days. Thus, whereas a wet, bare soil can lose $\frac{1}{2}$ inch of water in three to five days, it takes a mulched soil about six weeks to lose this amount, so that in hot climates a mulched soil can retain against evaporation much more of the water falling as rain than an unmulched.

The mulch also keeps the soil surface permeable. Rain-water can only reach the soil surface as a gentle stream of clear water, which causes a much smaller drop in permeability than if the soil surface itself was exposed to the beating rain. Thus, the mulch reduces the run-off of the rain and consequently reduces the amount of soil the water can carry away[2] and increases the proportion of the rain-water that percolates into the soil. Thus, not only is evaporation from the surface of the mulched soil reduced, but the amount of water infiltrating into it is increased. Hence, the water-supplying power of a soil can be considerably increased by mulching as is well illustrated by some of S. M. Gilbert's results on the mulching of coffee with banana leaves in Moshi, Tanganyika, given in Table 132.[3] The effect was large enough for the trees to be wilting on the clean weeded plots, but growing well on the mulched plots, at the time the first samples were taken.

The effect of mulches on the nitrate concentration in the soil is complex. During dry periods the increased moisture content under the mulch allows decomposition of the organic matter to continue with the production of nitrates for a longer time than in a bare soil, but once the rains come the increased permeability of the soil may cause the nitrates to wash out rather more completely than from the unmulched. Again Gilbert's results on coffee soils in Tanganyika illustrate this, for during the dry season the mulched soils, in which coffee was growing,

[1] I. de V. Malherbe, *Soil Fertility*, London, 1948.

[2] For an example of the effect of the weight of mulch applied on this control, see H. L. Borst and R. Woodburn, *U.S. Dept. Agric., Tech. Bull.* 825, 1942.

[3] *E. Afric. Agric. J.*, 1945, **11**, 75.

TABLE 132

The Effect of Mulch on Conserving and Maintaining the Water Supply in the Soil

Percentage moisture in the soil on the oven-dry basis

Depth of soil in inches	After prolonged drought			After a rainy period		
	0–6	6–12	12–18	0–6	6–12	12–18
Mulched plots	27·5	35·0	37·5	41·0	39·0	38·0
Clean weeded plots	15·5	22·0	26·0	30·0	33·0	32·5

had nitrate nitrogen contents from 30 to 200 per cent more than on the clean weeded land, but had the same, or even less, during the rains. However, these results are not always found, particularly when wheat or maize straw is used as mulch, as is becoming customary in the Great Plains and the prairies of North America, for on the whole these mulches reduce the nitrate content of the soil there.[1]

Mulches can have an important influence on the weeds growing in the soil. Thus, Gilbert found that banana trash reduced the labour required each year for weeding coffee from the thirty-five to forty days per acre needed for clean weeding, to eight to fourteen days, and further that undesirable grasses, which needed forking out, did not establish themselves under the trash as they did on the clean weeded areas.

The mulch also has certain general effects on the soil due to its organic matter decomposing. The moister conditions under the mulch favour the soil micro-organisms and probably the smaller animals as well, and the decomposition they bring about improves and stabilises the soil structure, as described on p. 419. This again helps to maintain the permeability of the superficial soil layer. The animals by their activity in the surface soil will also increase the number of the larger channels through which the water can leach. Further, the decomposition continuously sets free plant nutrients in the surface soil whenever it is moist. This decomposition must not, however, go on too fast, nor, in tropical regions where termites are common, should they consist of materials with too high a cellulose content, otherwise the mulch will soon disappear. Thus, relatively slowly decomposable material should be used, such as straw, for example. Gilbert has shown that, for coffee in Tanganyika, some grasses have little value as a mulch

[1] T. M. McCalla and J. C. Russel, *Nebraska Agric. Exp. Sta., Res. Bull.* 131, 1943; C. A. Mooers *et al.*, *Soil Sci.*, 1946, **66**, 307.

for this reason, whilst coarse material, such as banana slashings, are very valuable.

A further effect of mulches is that they increase the amount of exchangeable potassium in the soil, although the reason for this has not been established. Thus, I. W. Wander and J. H. Gourley[1] found that it was increased considerably to a depth of 8 inches in two years under a heavy straw mulch, and to a depth of 24 inches in twenty to thirty years. In the latter examples the soil under the mulch contained about 490 parts of exchangeable potassium per million of soil to about this depth, but fell rapidly to about a fifth of this value below it, whilst the exchangeable potassium in the unmulched soil fell to this value after a few inches. The extra potassium may have come from the straw, but potassium is the only mineral element showing this strong downward percolation. Further, a grass mulch, made by putting land down to grass and mowing it with a gang mower, such as is used on golf greens, and leaving the grass cuttings in place, also increases the available potassium in the soil. This method is used in many apple orchards, both in this country and overseas, and it causes the apple trees to take up much more potassium, and also more phosphate, from the soil than if the orchard is kept either clean weeded or sown to annual cover crops which are ploughed in.[2] Hence, this extra uptake of potassium, and possibly also of phosphate, appears to be a specific effect of the mulch due to some cause yet unrecognised.

These effects of mulches show the reasons why they are so valuable with shallow rooting crops in hot weather, for all these effects help to maintain the surface layers of the soil as a suitable environment for root growth. Indeed, for some of the very shallow rooting crops the root system tends to develop from the soil surface into the base of the mulch.

A surface mulch can have another very important function for use in helping to establish small seeded crops in hot climates, for the surface inch of soil is a very poor medium for seed germination if exposed to the heat of the tropical sun. This technique can be very useful in getting a grass or legume cover established on eroded or bare soils.[3]

Some of the benefits of a mulch can be obtained by growing shade trees which will protect the surface of the soil and low-growing crops from the direct heat of the sun and will to some extent break the fall of the raindrops before they hit the soil. Plate XXXIV gives a good

[1] *J. Amer. Soc. Agron.*, 1938, **30**, 438; *Proc. Amer. Soc. Hort. Sci.*, 1943, **42**, 1; 1945, **46**, 21. For similar results in short periods, see R. E. Stephenson and C. E. Schuster, *Soil Sci.*, 1945, **59**, 219; 1946, **61**, 219.

[2] See, for example, M. B. Davis and H. Hill, *Dom. Canada Dept. Agric., Publ.* 802 (*Tech. Bull.* 65), 1948; C. Bould *et al.*, *Long Ashton Ann. Rep.*, 1948, 37.

[3] B. H. Hendrickson and R. B. Crowley, *J. Amer. Soc. Agron.*, 1941, **33**, 690 (lespedeza in Georgia); G. E. Glendening, ibid., 1942, **34**, 797 (grasses in Arizona).

idea of the kind of intensity of shade used, in this case for coffee growing at 5,000 feet elevation in Kenya. The benefits from this practice of shade trees is difficult to assess, as several other factors besides shade are often involved. Thus, shade trees are commonly leguminous plants and hence they help to enrich the soil in nitrogen—if not through their roots, then through their leaf fall—and the practice of growing shade trees is often bound up with that of regularly slashing them and using the slashings as a surface mulch. Again, shade trees often act as windbreaks, and will therefore reduce the rate of transpiration from the protected crop during periods of strong drying winds. This practice has mainly been adopted in tea, coffee and cocoa plantations, all of which may have a shallow root system.

CHAPTER XXXVI

THE CONTROL OF SOIL FERTILITY IN PRACTICE

Problems in the control of soil fertility have been discussed in passing all through this book, and in this final chapter a few of the more essential conditions for fertility will be summarised.

The object of trying to increase, or to conserve, fertility is to obtain as large a yield as is economic, or as is possible, of whatever crops are grown; but high fertility often has the further consequence that it increases the range of crops a farmer can grow. Soil fertility naturally only plays a small part in the choice of crops, for the climate is the most important factor, and, in particular, the rainfall, the length of the frost-free period, and minimum night temperatures during the growing season. The control exercised by the first two are very severe. Drought and prolonged frost prevent large areas of the earth's surface being cultivated, whilst night frosts merely restricts the choice of crop. Again, unless there is a certain depth of soil, crop production becomes precarious, and this, together with the low temperatures and often high winds and heavy rainfall, prevents or severely limits the cultivation of large areas of mountain land over the world. These areas form examples of where the climate or depth of soil prevent crops making use of whatever fertility is stored in these soils.

A soil can only be fertile if it is a favourable environment for root growth. The roots of most agricultural crops need the following conditions for good development: they must have an adequate supply of oxygen and a low concentration of carbon dioxide; and the *p*H of the soil must lie in a fairly definite range, bounded on the upper side by the root's ability to extract nutrients from the soil, and usually on the lower by the concentration of certain cations such as aluminium and manganese, which are adsorbed under these conditions in sufficiently large quantities to harm the roots or the plant itself.

The oxygen and carbon dioxide needs of the root system depend on the soil temperature and the activity of the root system. There is no evidence that the root system is ever harmed by too high an oxygen content in the soil air, but it will most definitely suffer if the oxygen content falls too low. The principal exception to this rule is rice, whose roots need only very little oxygen in the soil air, for they appear to be supplied with it through special tissues in the stem and root. Most root systems do not seem to need carbon dioxide in the soil air, and most are harmed if it rises to more than a few per cent. But a moderate carbon dioxide

concentration, up to 1 to 2 per cent in extreme cases, can be very desirable in soils containing free calcium carbonate or much exchangeable sodium, for this helps to reduce the *p*H of the soil to below 8, or even below 7·5, at which *p*H the root systems of most plants can extract the phosphates and other minor elements they need. The actual carbon dioxide concentrations plant roots can tolerate depends to some extent on the root, but it also depends on the soil temperature, for the higher the temperature the lower is the concentration that begins to harm them.

A low oxygen content of the soil air, or a very low air content in the soil can have other undesirable consequences, for the microbial population in the subsoil will set up strong reducing conditions there, maintaining a high carbon dioxide concentration and producing reduced compounds, such as sulphides, which are very toxic to most roots. Thus, water-logging, a high water table, or a soil with such a fine texture that it has a very restricted air space are all undesirable; and most crops can only be profitably grown on soils in which water-logging is prevented, and a high water table lowered by drainage. One can do little to improve fine textured soils with a very small air space, except restrict the cropping to those crops that suffer least from this condition.

Low oxygen and high carbon dioxide concentrations in the soil air and water also affects the composition of the organisms inhabiting the soil, for only groups tolerant of anaerobic conditions can make active growth, or even exist at all, and these groups are mainly confined to the bacteria. The more general aerobic population will be confined to the surface of such soils, and the composition of its larger members will be restricted because they cannot escape unfavourable climatic conditions of heat, cold or drought by penetrating into the subsoil. Thus, most species of earthworms are absent from such soils.

Another harmful consequence of poor drainage in arid regions is that the quantity of salts in the soil begins to become sufficiently high to affect plant growth, and often to restrict very considerably the species of plants which can grow. Not only may the salt content rise, but so may the content of exchangeable sodium ions, with the consequence that the soil may become very alkaline, badly aerated and difficult to drain.

The *p*H of the soil affects the root system mainly indirectly, for the root or plant suffers from consequences of the *p*H before the actual hydrogen- or hydroxyl-ion concentration has any harmful effect. Thus, few roots can absorb enough phosphate, iron, zinc or manganese from the soil with a *p*H much above 8 for the plant's needs. And at low *p*Hs the root system suffers from poisoning by soluble aluminium and

manganese ions on the one hand, and from shortage of available calcium ions on the other, before the hydrogen-ion concentration begins to be harmful.

Thus a soil can only be a suitable environment for plant roots if it is adequately drained and aerated, if its salt content and content of exchangeable sodium ions is low, and if its *p*H falls in a suitable range. Hence, drainage and dressings of lime or of sulphur or gypsum may be necessary to bring a soil into a suitable condition for good root development. If these conditions are not properly fulfilled the choice of crop will be unduly restricted, and so will its root system. Hence, it will be liable to suffer from frosts, droughts and high temperatures that would not affect a deeper root system, and these harmful effects are all more serious in hot regions than in cool, and particularly in moist, cool regions, for under such conditions a shallow root system may be able to carry a full crop because at no time will it have to build up an appreciable water deficit in the soil.

The root system needs not only a suitable environment in which to grow, it must also take up enough water and nutrients for the crop to give a good yield of whatever part is required. Of the nutrient shortages that limit crop yields over the world as a whole, nitrogen and phosphorus are the most important, though lack of available calcium and potassium are also important.

Lack of water probably limits the total food production in the world more than any other single factor, although it is relatively unimportant in a humid country such as Great Britain. It is directly responsible for the sterility of the deserts, and for the very low yields and restricted choice of crops in the semi-deserts and steppes.

Drought only begins to affect plant growth appreciably when the root system has extracted all the readily available water from the soil in the root zone, by which time it has also extracted some from the soil below. The deeper the root system, and the more thoroughly it ramifies through the soil, the greater is the amount of water it can withdraw from the soil, and the longer the crop can withstand a drought without suffering. There are very few methods available for deepening the root system of the plant. Lowering the water table and incorporating lime in the subsoil are both helpful if water-logging or acidity limit the depth of root penetration. Breaking up a hard pan is also helpful, but just how indurated or compact a pan must be before the roots cease to be able to penetrate it is uncertain. A pan may harm the root system more by impeding the drainage of water, and hence allowing reducing conditions to prevail and the carbon dioxide content to rise to too high a level, than by it actually preventing the roots penetrating through it. Again, in heavy clay soils the root system cannot always ramify through

the clay uniformly enough to extract all the available water in the root zone, and it is possible that in such circumstances deep tillage may encourage this ramification, but the technique for doing this has not yet been established.

Very little can be done to increase the water-holding power of the soil, for even large additions of bulky organic manures have little effect, and probably can never have an effect greater than would correspond to deepening the root zone by 6 inches. But they can have a very important local effect, for an extra small amount of water, in the neighbourhood of a seed or a young plant during a drought, may allow it to rapidly deepen its root system at this critical time.

But the removal of water from the soil by the crop is only one side of the water régime: it is equally important to allow sufficient water to penetrate into the soil for crop growth. This is the problem of maintaining the surface of the soil in such a condition that rains, even if they fall as torrential storms, shall be able to penetrate into the soil whenever necessary. This maintenance of surface permeability is undoubtedly one of the most difficult problems farmers have to face in regions subject to such storms. This does not mean that, for as far as the farmer is concerned, all the rain must enter the soil, for as soon as the water deficit in the soil has been made good it may be desirable for most of the remainder of the water to run off, provided it does not remove too much soil, for unnecessary leaching of water through the root zone removes the nitrates from the soil, and hence wastes some of the soil's store of available nitrogen. Run-off may complicate the job of the engineers in the river catchment boards, in that flood control is the more difficult the quicker the surplus water finds its way into the rivers. However, efficient drainage systems may give them just the same problems, for storm-water rapidly percolates through most well-drained soils into the drains.

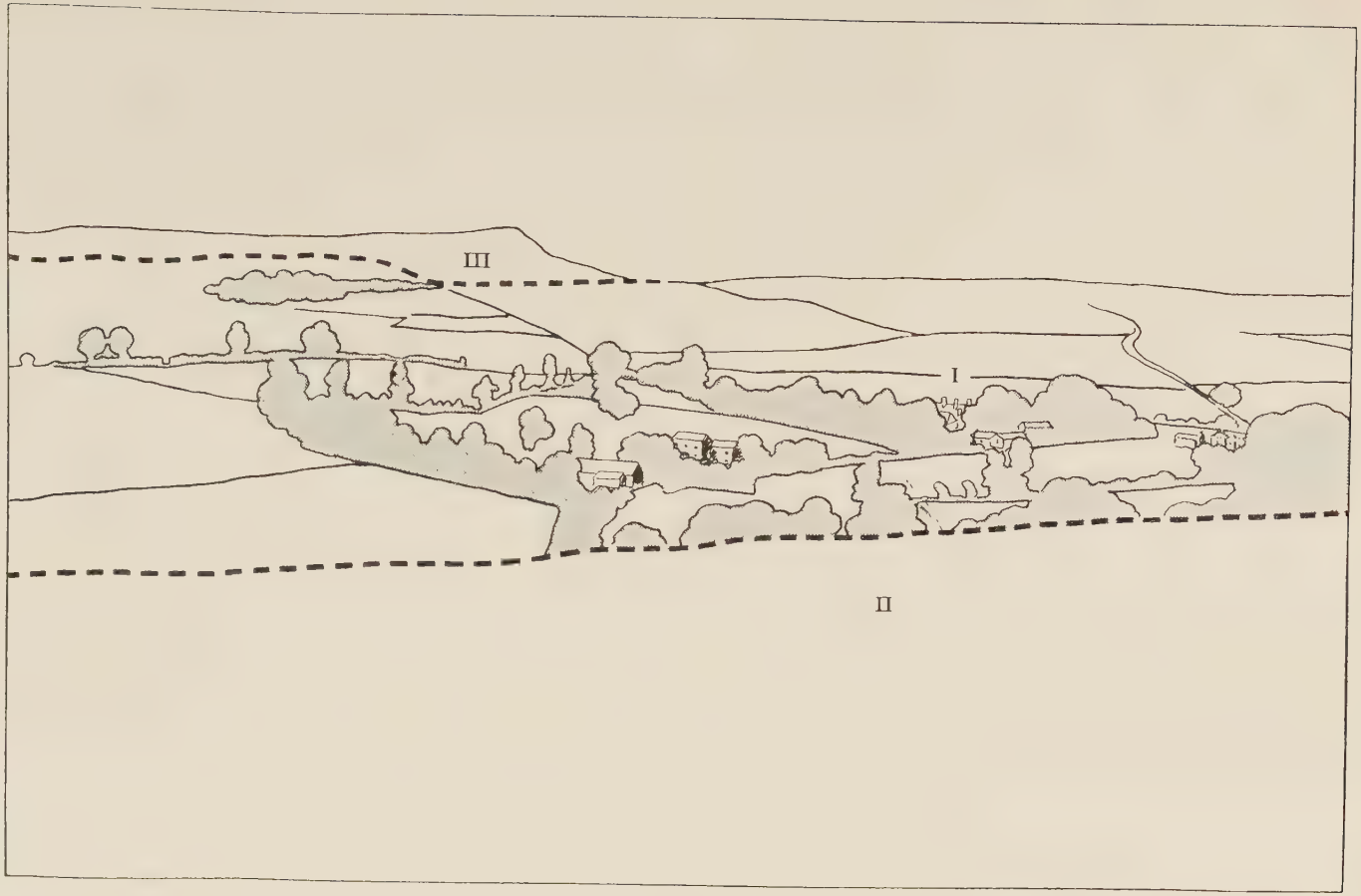
Nitrogen and phosphate probably are the two plant foods that most limit crop yields in regions where water is not the limiting factor. Phosphate shortage occurs in areas all over the world, and may limit yields even in dry areas, as, for example, in the wheat-growing districts of Australia. Shortage of available nitrogen is characteristic of the humid regions, although A. E. V. Richardson[1] considers that even in some semi-arid regions shortage of nitrogen is as important a factor as shortage of water in causing the low yields obtained. Recent field experiments all over the world have consistently shown how once water is plentiful, crop yields can be increased, sometimes very markedly, by adding available nitrogen compounds to the soil. In fact, in many soils and for many crops, the nitrogen level in the soil is the most

[1] With H. C. Gurney, *Emp. J. Exp. Agric.*, 1933, **1**, 193, 325.

Poor grass pasture on acid London Clay, untreated (*top*) and dressed with 10 cwt. per acre of ground rock (Gafsa) phosphate (*bottom*). Phosphate given February 1918, pasture photographed August 1919 at Horndon-on-the-Hill, Essex

(*p. 598*)

The Ross Lowlands from the slopes of Linton Hill, looking west towards Penyard Hill and Ross
(*p. 606*)



The classification of the land in the photograph

Category I: The large arable fields with sandy loam soils on gentle rolling topography
Category II: The foreground shows land having rather a steep slope and a shallow soil, which is carrying a patchy crop probably because of drought
Category III: The steep wooded slopes of Penyard Hill, in the background

Mixed cropping with cassavas and bananas in an improved agricultural rotation in the Belgian Congo

Forest invading an old cassava and banana field, to begin the forest fallow which will last for several years. Some forest trees are allowed to remain on the land to give shade and regeneration (Belgian Congo)

(*p. 602*)

important factor controlling the crop yield.[1] But nitrogen differs from phosphates in that if the phosphate status of the soil is low, a phosphate fertiliser must in general be added, whilst if the nitrogen status is low, either leguminous crops can be grown, which directly increase the amount of available nitrogen compounds in the soil, or nitrogen-poor but otherwise readily decomposable organic matter can be added so that the nitrogen-fixing bacteria in the soil can increase the supply, or the soil surface can be left wet so nitrogen-fixing blue-green algae can develop. Of these three mechanisms, the first is of very great agricultural importance, the second is probably mainly of importance in forests and in some pastures, and the third probably only in paddy rice fields. But it is not always profitable to rely entirely on biological methods for increasing the nitrogen supply of the soil, and the need for nitrogen fertilisers is rapidly being appreciated all over the world. There is little doubt that crop yields in the humid regions could be considerably increased if the farmers could be persuaded to adapt their systems of farming for making the best use of these nitrogen fertilisers.

The conservation of fertility usually involves, on the one hand, putting back into the soil the nutrients removed by the crop or leached out by drainage water, and on the other preventing any appreciable movement of the soil. Fertility cannot necessarily be maintained merely by putting back all the crop residues even if this is possible, for this does not replace the losses by leaching. But proper conservation, and the return of all crop residues and of the excreta of animals feeding on the crops, reduces the drain on the reserves of plant food. In areas where the temperature and rainfall are high, and the minerals composing the soil particles are weathering fast enough to provide much of the minerals needed by the crop, a stable system of farming, for as far as nutrients are concerned, can be assured if an adequate number of leguminous crops are taken.

Another method of ensuring stability of nutrient status, which can only be practised in the valleys of certain rivers, is to allow fertile silt carried by the river to be deposited on the land. Thus, much Egyptian soil has been kept fertile for several millenia by plant nutrients derived from the weathering and erosion of rocks in the Abyssinian highlands. Here is a case where the most efficient way of tapping the plant nutrients produced may not be to grow crops on the site of their production, that is, on the thin soils of the high mountains, but to let these materials be washed down into the deep alluvial soils of the valley.

The prevention or at least the control of water erosion on agricultural lands depends on keeping the soil surface permeable, and ensuring that whatever water cannot penetrate the soil runs off the surface

[1] See, for example, H. L. Richardson, *Emp. J. Expt. Agric.*, 1946, **14**, 1, 109, 175.

slowly as a thin uniform sheet. This control may involve developing a suitable method of farming to ensure that the soil surface is protected from the actual falling raindrops, and that enough decomposable organic manure is used, or long enough leys are taken, to ensure the water-stability of the crumb is as high as possible. Strip cropping on the contour, sometimes with terraces, is often the method to be used, and here, as in the prevention of wind-blowing, the mouldboard plough can be a very undesirable cultivation implement because of the bare soil surface it leaves.

The prevention of wind-blowing consists in preventing the wind blowing across long lengths of bare, unprotected soil. The soil can be protected by planting quite narrow strips of crops across the direction of the strongest winds, of cultivating the soil so that as much as possible of the previous year's crop residues are left on the surface of the soil, or are anchored into the soil with most of the residues being above the soil. Or it can be protected, but not very effectively, by running ridges across the direction of the wind. None of these methods, however, give much protection if the land is subjected to a drought lasting several years.

Soil organisms and soil organic matter usually only affect crop growth indirectly. One of the principal consequences of the soil organisms feeding on the soil organic matter is the continuous conversion of nutrients from a form in which they are relatively immobile and unavailable into one in which they are mobile and available to the plant. The organic matter is an excellent reservoir of all plant nutrients, and in this form they are relatively immobile in the soil, and the soil organisms slowly release the plant nutrients from the organic matter into a mobile form that is available for the growing crop. Besides this primary function, some organisms have other functions, such as the mixing of the dead plant litter that falls on to the surface of uncultivated soil with the superficial layers of the soil—one of the principal functions of the surface-feeding earthworms.

The soil organisms have another function, the details of which are not fully understood, which is the mellowing of the soil crumbs in clay soils, and the binding together of sand particles in light soils. They either produce, as a by-product of their metabolism, chemical substances that bind the soil particles together, or they bring the soil particles and organic substances into intimate contact with each other. This increases the stability of the distribution of pore sizes during wetting, and the resistance of the soil crumbs and clods to break-up by slaking. Hence, they help to improve and maintain the permeability of the surface soil and the goodness of aeration in the subsoil during wet periods. By mellowing the tilth of the clay soils, the clods crumble more easily,

and by binding together the sand and silt particles, sandy soils are less liable to blow and to cap.

The general soil organisms have another important action in that they tend to kill any organism not adapted to life in the soil, and since few of the plant pathogenic organisms are so adapted, the general population plays an important part in the control of many plant diseases.

The Management of Sandy Soils in England

The general problems facing the light- and heavy-land farmers in England will serve as an illustration of the principles just discussed. The great problems facing the light land farmer are to obtain enough water in the seed-bed for the crop to get started, to provide an adequate amount of plant food in such a way that it will not get washed out of the soil too quickly, and, in some places, to prevent the soil blowing.

The best way of increasing the water-holding power of the seed-bed, and also of maintaining an adequate supply of nutrients without too great a loss by leaching, is to maintain as high a level of organic matter in the surface soil as possible. The old method of doing this was to fold sheep over the land. Between two and four green crops might be taken during twelve to twenty-four months, and each would be eaten off by sheep and then this was followed by two or more years in arable crops. The sheep and the green crops not only added organic matter to the soil, but the sheep compacted and often puddled the surface layer of the soil. This somewhat increased the carbon dioxide content of the soil air, which is of importance on all light soils containing free calcium carbonate, as it helps to reduce the *p*H of the soil, and hence increase the availability of some of the plant nutrients.

The main problem at the present time on many of these soils is to develop a system of farming which is adapted to present-day economic conditions and which is technically as satisfactory as the sheepfold. Leys left down for several years and grazed with cattle are technically as satisfactory as the sheepfold, but they often involve fencing and watering large areas of land, sometimes in districts where water is scarce. The fibrous roots of the ley will often bind soil particles together for three to four years after it has been ploughed out.

Another aspect of the problem of conserving water at sowing or planting time is weed control, for light land encourages both deep-rooting weeds and weeds that multiply from a spreading root system or from underground rhizomes. Weed control may be particularly troublesome during winter on light land compared with heavy, because light soils are so much better aerated than heavy that weeds grow in them for a longer period in the late autumn and early winter,

and start growing again earlier in late winter and early spring; and in a number of years weeds will, in fact, make appreciable growth throughout the whole winter. These weeds can be killed or set back by suitable cultivation before the seed is sown, but in a dry spring the process of doing this may dry out the surface soil so much that the seed cannot germinate until after the drought has broken. An important principle in weed control in areas of adequate rainfall is to keep the land cropped, for the crop, even if only quite small, discourages many weeds. These catch crops not only help to control weeds, but they also prevent the leaching out of nutrients, reduce the liability of the soil to blow, and add a little more organic matter to the soil, when they are ploughed in. Catch-cropping is therefore an integral part of light-land husbandry whenever the rainfall is sufficient, and is, in many parts of the country, confined to light land. In the days of the sheepfold these would always have been fed off, but now they are often ploughed in.

The secret of light-land farming is therefore to prevent weeds multiplying on the land, for it is much easier to get a moist seed-bed in dry weather when there is no necessity to have to use weed-killing operations such as ploughing or deep harrowing—operations that cause a large loss of water from the surface soil by evaporation.

Finally, light land can suffer from over-liming very easily. Ideally light land should have a *p*H between 6 and 6·5, and whenever it is necessary to lime it should be given in small dressings, at frequent intervals if necessary, but one should never aim at bringing the *p*H up to 7.

Thus, one can summarise the problems of the light-land farmer as maintaining the humus content of the surface soil as high as possible, keeping a growing crop on the land for as large a part of the year as possible, and keeping the land so clean that the absolute minimum of cultivations are necessary to get a seed-bed free from weeds whenever the weather is dry.

The Management of the English Clay Soils

These soils present an entirely different set of problems from the sands. The two great difficulties in clay-land farming are to keep the soil as dry as possible during the winter six months when transpiration is low, and to obtain a suitable tilth for drilling seeds at the appropriate times of the year. The effect of improving the drainage on the stand of young wheat or beans through a wet winter can be most striking, and an efficient drainage system and deep cultivations help to ensure that the surface soil is well drained and well aerated throughout this season. The importance of this is obvious, for, on the one hand, waterlogging keeps the root system very shallow and poorly developed, and

hence causes the young plant to be partially starved of nutrients, and, on the other, water-logged soils heave badly during frosts and so break a large proportion of these poorly developed roots.

The English clay soils fall into two sharply contrasting classes with respect to their ease of drainage. The genuine clays have normally a fairly good stable subsoil structure, and a properly installed drainage system will function efficiently for a long time, since there are a large number of stable drainage channels. The silty clays, which may easily be mistaken for the true clays on a cursory inspection, are so high in silt that they do not possess a stable subsoil structure nor stable drainage channels through the subsoil. Hence, it is much more difficult to get the water into the drains, and the water that enters is silty, so that the drains will soon be blocked with silt unless proper steps are taken to trap the silt. These soils are probably some of the most difficult to manage in the country, and the only way it seems possible to improve them is to lay them down to long leys and then to take a few arable crops while the subsoil is still well supplied with drainage channels formed by the roots of the ley.

Clays also differ from the sands in the ease of cultivation. Sands can be cultivated on almost any day of the year, and rarely are there any problems in getting a tilth suitable for sowing, provided there is enough moisture for the seed to germinate. Clays, on the other hand, can only be cultivated when the moisture content of the soil lies between comparatively narrow limits, and if it is cultivated at the wrong time, or in the wrong way, the surface will be composed of large lumps that are plastic when wet and hard when dry, and that cannot be comminuted into crumbs of a suitable size for a seed-bed. Hence, the primary problem of the clay-land farmer is to choose the right time and the right implement to do his cultivations, and since there are only a limited number of days during which cultivations are possible, he needs more and heavier cultivating machinery per 100 acres than his light-land colleague. Cultivating heavy land when it is moist, and leaving the clods exposed to the sun, wind, and rain, and in particular to the frost, help to produce a crumbly layer of soil on the surface; and if one wants to prepare a seed-bed, it is essential that no deep cultivations are done once this tilthy layer has begun to form.

Most of the English clay soils are naturally low in phosphate. Thus, even if the surface soil has received generous dressings of phosphate, deep ploughing, by bringing up fresh subsoil, may cause crop failures unless the phosphate deficiency of this subsoil is rectified. Again, much of the clays had been in pasture for many years before the 1939–45 war, during which time they received very little phosphate. As a consequence, they were so short of phosphate that, when the pastures

were ploughed out during the war, arable crops would fail unless generous dressings of phosphate were given, much to the surprise of many farmers who had expected to cash the fertility stored up by the grass. Even the pastures themselves would have been improved if they had received adequate dressings of phosphate, as is shown in Plate XXXV, which illustrates the effect of adding, in this case, ground rock phosphate to a typical phosphate-starved acid pasture on the London Clay in Essex.[1] The phosphate encouraged the development of wild white clover and the good pasture grasses at the expense of such poor grasses as the bents (*Agrostis*) and *Aira caespitosa.*

Heavy land holds much more available water than very light land, but, even so, seed-beds in the spring can easily be dried out if they are over-cultivated during drying periods. Hence, again, the great value of preventing weeds growing or germinating in the seed-bed, and the value of general good management which helps to ensure this.

Nutrient levels can be maintained more easily in clays than sands, for they hold the nutrients much more retentively against drainage. Clay soils also are never as well aerated as sands, so the *p*H of even a calcareous clay never rises high enough to affect the availability of phosphates or of trace elements. Hence, clay soils cannot be over-limed, and in fact the mellowness of the tilth is often said to be improved by very heavy dressings of chalk. Again, the humus content of heavy soils is of less importance than on light, for whereas it is practically impossible to farm many sands without regard to the humus and fibre content of their surface soils, it is perfectly feasible to farm clays, apparently indefinitely, without the use of farmyard manure or leys.

The importance of farmyard manure, leys, and lime or chalk in helping to improve the crumbliness or mellowness of clay clods or crumbs in practice is still undecided. Farmers have successfully farmed clay lands without adding humus or fibre to the soil, and without ensuring the presence of free calcium carbonate in the soil, though this success may only have been achieved by men who are very skilful cultivators.

Clay lands are often spoken of as cold soils, and certainly crops make much less growth during the six winter months on clay soils than they do on sandy soils in the same district. Thus, catch-cropping is impracticable on clays, and winter-sown crops must often be sown one or even two months earlier on clays than on sands if they are to make enough growth to stand the winter frosts. In the same way, spring-sown crops must often be sown considerably later on clays, because they are still too cold and wet for seeds to germinate, although conditions on the lighter soils are passable. But the cause of this shorter growing season

[1] G. Scott Robertson, *J. Min. Agric.*, 1922, **29**, 519, 600.

may be the poorer aeration rather than the lower temperatures of wet clays compared with sands.

Clay soils have had rather a chequered agricultural history. Originally covered with oak forest and hazel undergrowth, they were early reclaimed for agriculture purposes by draining, applications of lime[1] and, later, of ground bones. Wheat and beans were the great clay crops, and in the early part of the last century, under the combined influence of high prices, large drainage schemes and artificial stimulus to enclosure, great areas came into cultivation, so that now only little unreclaimed clay remains, excepting where the forest was preserved for hunting. Crops grew well but ripened late; a wet harvest was a terrible calamity. Bare fallowing was always necessary once in four years, and any of the intervening years might, if wet, be lost by the difficulty of getting on the land to sow the crop. When the price of wheat fell in the eighties of the last century many of these soils went out of cultivation and became covered with a mixed growth of grass and weed, which was grazed by stock and gradually deteriorated as the old drains choked up and the land became more and more water-logged. *Aira caespitosa*, bent grass (*Agrostis vulgaris*), yellow rattle (*Rhinanthus Crista-galli*), and in drier places the quaking grass (*Briza media*) and ox-eye daisy (*Chrysanthemum leucanthemum*) are among the commoner plants on these neglected fields; after continued neglect thorns and other trees spring up and the land reverts to wild woodland; the only relics of the past are the field names and the high ridges or "lands" made years ago to facilitate drainage. But much of this rough land has recently been improved and converted into useful pasture or arable land by attending to the drainage, and to the lime and phosphate status of the soil on the one hand, and by the introduction of the crawler tractor and heavy cultivating implements on the other.

Thus, the problems of clay-land farming are keeping the surface soil well drained during the winter, and having an adequate amount of machinery available so that as much of the land as possible can be cultivated when it is in a condition to fall down easily to a crumbly condition. Heavy-land farming should, therefore, be power-farming wherever possible.

Some Principles involved in the Management of Tropical Soils

The management of tropical soils involves quite different sets of principles from English soils, because both the climate and the soils are different. In the tropics there are no marked seasonal changes of

[1] For example, see *The Inrichment of the Weald of Kent*, by R.I., 1625 (attributed in the 1636 and later editions to Gervase Markham).

temperature, such as occur between winter and summer in the higher latitudes, so the soils there usually have a more even, and a considerably higher average temperature. The rainfall, again, in the tropics has a different distribution from that in the temperate regions, for the rain tends to fall in heavy storms, and to be confined to one or to two rainy seasons in the year, with intervening dry seasons of severe drought. Further, as the annual rainfall increases, so usually does the length of the rainy season with a corresponding shortening of the dry.

The leached soils of the tropics differ from those in the temperate regions by the much higher proportion of kaolinite clay they contain. If the parent material is low in iron and aluminium, and the site is ancient and uneroded, kaolinite clay may be practically the only mineral present in the soil, and such soils will have a poor, unstable structure and a very low base exchange capacity. But if the parent material contains much iron or aluminium, then the soil will contain their oxides and hydroxides, which will cement clusters of kaolinite particles into firm and larger aggregates, thus improving the soil structure and permeability, though often at the cost of increasing the power of the soil to fix phosphates. Further, the subsoil of such soils may contain these hydroxides in such a form that it is fairly soft and plastic in its natural condition, but dries out into hard bricks that only weather down very slowly to a friable soil when exposed to the sun.

The basic principle of managing these soils is, therefore, to devise a system of farming that involves the minimum of clean cultivation—for this leaves the soil bare—and that maintains a high organic matter content in the surface soil—for this not only helps to hold bases against leaching and phosphate against fixation by the active iron and aluminium compounds present, but it is also a source of plant nutrients in itself and it helps to maintain the structure and permeability of the surface soil.

The problems involved in cultivating a soil with a minimum amount of clean cultivation are still largely unexplored in the humid tropics. Methods of soil cultivation under a surface mulch, similar to the stubble mulch techniques that are being developed in the wheat lands of Canada and America, may be found applicable; but the best basis for future developments may be that underlying traditional native agriculture, namely, mixed cropping, in which the land carries crops planted and coming to maturity at different times, and of dibbling or planting the crop into a soil that has only received a very shallow cultivation with a hoe.

Soil organic matter and soil structure can be maintained in some areas by the use of farmyard manure and composts, but the dressings

of manure needed are so high, up to 30 tons per acre annually,[1] that this method is mainly confined to vegetable gardens. However, it can also be maintained in land under permanent plantation crops by leaving, as a mulch on the soil surface, slashings from trees or crops grown and cut largely for this purpose (p. 588).

The usual method of maintaining soil organic matter is, however, to use an alternation of a few years of tillage crops with a few of soil-resting crops, that is, crops not requiring any cultivation. This method is therefore similar in principle to that of alternate husbandry in England, but it differs greatly in detail. It may be very similar, for provided the soil is adequately supplied with nutrients, or adequate amounts of fertiliser are used, and there is an adequate rainfall, then the land can be put down to grass for a period of years. These leys are usually planted, not sown, but they differ from temperate leys in that there are not yet any tropical pasture legumes corresponding to the clovers and lucerne of the temperate regions. In East Africa, grasses of the *Pennisetum* and *Cynodon* genera are often used, including elephant (*P. purpureum*) and Kikuyu (*P. clandestinum*) grasses. These leys are down for 3–6 years and their primary function is to restore the structure of the soil: they are most valuable if they are planted before the structure has deteriorated too badly.[2]

The much more common way of putting land down to a resting crop is to let it revert to natural vegetation, which will be a grass or savannah (grass with bush) type in the drier[3] and a forest type in the wetter regions—a practice commonly known as *shifting cultivation.* The problems of importance here are to ensure that a desirable type of natural vegetation is quickly established, that is, one which covers the soil surface, increases the organic matter content and nutrient status of the soil and improves its structure as quickly as possible, and one which can easily be killed when the land next comes into arable. On the whole a desirable type of vegetation usually regenerates if the land was well managed and its condition was still reasonable at the end of the arable break, whereas undesirable species, such as the *Imperata* type of grass, come in if the land is left in too poor a condition. Further, the last crop planted may influence the rate of establishment of the desirable species. Thus C. E. Kellogg[4] quotes the findings of workers in the Belgian Congo that in some areas bananas and cassava encourage the

[1] For an example of the efficacy of dressings of this order in Kenya, see M. D. Graham, *E. Afric. Agric. J.*, 1945, **11**, 3.

[2] M. D. Graham, *E. Afric. Agric. J.*, 1945, **11**, 3, has given an example from Kenya of a rotation based on leys like this.

[3] This practice is sometimes referred to as fallowing, but is entirely different from the European practice of bare fallowing, which, naturally, must not be practised in these regions.

[4] *Soil Conservation*, F.A.O. Agricultural Studies No. 4, 1948. This bulletin describes some of these shifting cultivation practices.

rapid regeneration of forest, which is wanted, whilst groundnuts encourage sparse, and therefore inferior savannah that is only slowly invaded by the forest.

The re-establishment of the natural vegetation takes place quicker if the cultivated areas are either small plots or narrow strips surrounded by the natural vegetation. Small plots are customary in much native agriculture, but long narrow strips allow a more systematic and intensive use of the land, and at the same time can give better protection against erosion. Kellogg, in the F.A.O. bulletin already quoted, has described such an improved system of shifting cultivation that is being developed in parts of the Belgian Congo, and two of his photographs illustrating stages in this system are reproduced in Plate XXXVIII. The first shows a mixed crop of cassava and bananas, with the natural forest in the background and the second shows the forest invading a strip after the last harvest has been taken.

The number of years the land must be left in a resting crop depends on the poverty of the soil and the goodness of management during the tillage period. Very impoverished soils, such as occur in the wetter areas where forest is the natural vegetation, need a longer rest than soils with a higher reserve of plant nutrients, such as often occur in the drier areas where grass or savannah is the natural vegetation. Hence 3–6 years in grass is often sufficient, whilst 10–20 years in forest may be necessary. Such short periods in grass are, however, only effective if its grazing or burning is controlled, for if the grass is grazed too heavily, it cannot develop a deep or extensive root system, hence cannot bring up plant nutrients from the deeper layers of the subsoil, nor add sufficiently large quantities of organic matter to the superficial layers of the surface soil to improve the structure. These methods have therefore the consequence that they can only be effective if the land is neither over-populated with stock nor human beings, for over-grazing renders the resting period largely ineffective in restoring the soil condition, and over-population prevents the land being kept out of cultivation long enough for this restoration to take place.

The problem of bringing land back into cultivation after the resting period is usually solved by firing the vegetation when it is dead, preferably at the beginning of the rains, if it is mainly grass; and cutting it down and burning it, if it is forest. Presumably burning the vegetation, particularly the grass, is rather a wasteful operation, but the problems involved in composting it are considerable. In the first place it mainly consists of cellulose and lignin, a great proportion of which must be oxidised away before the nitrogen content of the compost is high enough for it to be put on the land, and in the second place termites may use much of the more cellulosic material as food, so becoming much too numerous.

A considerable amount of work has now been started on the manuring of tropical soils. They are typically low in plant nutrients and lime, but crops often do not show the increases of yield one would expect from the apparent deficiencies in the soil. Too little systematic work has been done on the manuring of the different types of tropical soils for any general statements to be made, though the following may be valid over considerable areas. The soils are acid and low in exchangeable calcium, yet the yields of most crops are not usually increased by liming. The principal use of lime may be to increase the amount of nitrogen fixed by tropical legumes, for these can be made to increase the nitrogen level in the soil if they are used as shade trees and lopped, or as green manures and ploughed in, or fed to animals and the manures so produced put on the land. The soils are short of phosphates, and though superphosphate increases crop yields considerably on some soils,[1] it has little effect on others, possibly because the soluble salts it contains release too much aluminium into the soil solution. It is possible that ground rock phosphate, such as is being mined in Uganda, will be found a satisfactory source, although in soils which fix phosphate very strongly it may have to be mixed with farmyard manure or compost and even then, for some crops, may have to be converted into an available form by being taken up by a previous crop which is then either ploughed in or fed to animals and applied as farmyard manure.

The two general aims of crop husbandry in the tropics thus seem to be to keep the soil surface protected from the sun and rain for as long as possible each year, and to choose a system of management in which some of the crops grown will enrich the surface soil in plant nutrients and allow its structure to regenerate after it has begun to deteriorate under tillage crops. The former is achieved by mixed cropping, by methods of planting not involving much cultivation, by methods of weed control based on suitable rotations rather than on clean weeding, and by the use of mulches, cover crops and shade trees. The second is achieved by converting the maximum amount of unwanted plant and animal refuse into manure and compost, by the use of adequately manured leguminous crops, and by the control of the rate of regeneration of the natural vegetation, and its type, through the use of suitable rotations and a proper lay-out of the cultivated and resting areas.

The Principles of Land Classification

The preceding summary of the factors controlling the fertility of the soil is directly relevant to problems of land classification. The object

[1] For some striking examples of the effect of superphosphate on crop yields in Nigeria, and its apparent residual effects for over five years, see M. Greenwood, *Commonw. Bur. Soil Sci., Tech. Comm.* 46, 170, 1949.

of land classification is to help in classifying the possible uses to which the land can be profitably put, whether it be merely to decide how far a specific crop can be taken, whether arable or grass farming should be used, or whether it should be used for forestry, for amenity or for urban or industrial development. Problems in land use planning do not come within the scope of this book, and this discussion will be limited to problems bearing directly on the use of land for crop production.

The basis of land classification should be furnished by the soil survey, provided it is detailed enough. The maps and descriptive texts published by the American and Canadian Soil Surveys furnish excellent examples of the way this can be done in practice. But it is often desirable to condense the mass of information available to show the suitability of the land for crop production,[1] and for this purpose various methods of productivity or fertility ratings have been developed, by which soils can be put into various classes, or given a quantitative rating, as a measure of its desirability for arable farming, grassland or forest.

The suitability of a piece of land for crop production depends on three groups of factors: those entirely beyond the control of the farmer, those requiring expensive capital development, often on a co-operative basis, and those dependent on the normal changes that a farmer can bring about year by year.

The first group of factors include the climate, the topography of the land, the depth of the soil, and the material composing the soil. Thus, the uses to which steep slopes can be put are far more limited than those for level land, and are confined to forests and pastures. The depth of soil again limits land use severely. Shallow soils, particularly if they contain many boulders or rock exposures, again become unsuited to arable farming. The type of material forming the soil, in particular the size distribution of particles, whether the soil is a sand, loam or clay, is important; so is the actual composition of the particles, whether they are mainly organic or inorganic, whether limestone or chalk is a prepondering constituent, and under some climatic circumstances whether the minerals weather fast enough to produce an appreciable supply of any plant nutrient. None of these factors can be controlled to any extent: the farmer must choose a system of farming adapted to the limitations these factors impose on him.

The second group of factors are mainly two—drainage and irrigation. Both of these often involve control over a large area of land, and hence are primarily under communal rather than individual control. If

[1] For a summary of the methods that have been in use, see G. V. Jacks, *Imp. Bur. Soil Sci., Tech. Comm.* 43, 1946.

communal control is poorly developed, then impeded drainage, waterlogging and drought constitute factors of the first group, which are outside the farmer's control, and which severely limit the types of farming he can practise. However, these factors are not necessarily entirely under his control, for impeded drainage due to impermeable clays, or to impermeable hard pans or clay pans developed over large areas of country, must still be regarded as a limitation imposed on the farmer and in the main beyond his control. Accumulations of soluble salts in the soil also come within this category, for if the drainage can be made good, and good water is available, these salts can be washed out of the soil. These reclamation operations are not normally recurrent; once done, less costly routine operations normally suffice to maintain the improvement in the soil conditions brought about.

The third group of factors include conditions such as the nutrient status of the soil and its acidity. They differ from the second group in being under the control of the individual farmer, but they are like the second in that the farmer cannot alter them permanently. Thus, soils that are naturally acid, and derived from an acid parent material, can be neutralised by adding lime, but in course of time this lime is leached out of the soil and the original acidity shows itself again. The same applies to the potash, phosphate and nitrogen reserves, and sometimes to the reserves of other nutrients as well.

Two types of methods of grading land have been developed: one based on potential, and the other on actual performance. In the first type of method, attention is paid to the factors affecting fertility beyond the control of the farmer, namely, those in the first, and sometimes in the second, of the above groups. A simple classification of agricultural land into three categories has recently been used by D. A. Osmond and the West Midland Planning Group.[1] These categories are:

Category 1. Highly productive under good management. The site must not be too elevated; be level or gently undulating; have a favourable aspect. The soil must be deep; have favourable drainage status (actual or potential), moderate texture, usually loam, but including some peats, sands, silts and clays.

Category 2. Medium quality land, whose productivity is limited by one or more factors of site or soil being unfavourable. Thus, the site might be too high, too steep, or have an unfavourable aspect; or the soil may be too shallow, or inadequately or excessively well drained.

Hence, this group contains the heavier clays and lighter sands, providing the other factors are not too unfavourable.

[1] See *English County*, London, 1946; *Land Classification in the West Midland Region*, London, 1947.

Category 3. Land of poor productivity because of the extreme operation of one or more factors of site or soil.

An example of these three categories of land can be obtained from Plates XXXVI and XXXVII, which show a typical Herefordshire landscape and the classes of land it contains. The Land Utilisation Survey, using the same kind of criteria, have adopted ten productivity classes.[1]

The other method of grading the productivity of the land is to compare the average yields of crops actually obtained on it with the average yields on land accepted to be very fertile or to be of average fertility. The difficulties of this type of classification are twofold. First, the productivity rating depends somewhat on the crop chosen, for the relative fertility grades of different soils would not necessarily be the same if barley was chosen as the test crop, or if wheat was. This limitation can obviously be overcome by comparing the yields of several crops and weighting the comparisons suitably. The second difficulty is much more serious, for it involves the skilfulness of the farmers' management. A good farmer will obviously obtain higher yields than an indifferent one from the same soil, and this will not merely be due to the use of more fertiliser and other aids to high fertility; it will also be due to the use of better methods of cultivation and weed control, and in always being abreast of his work and never behindhand. It would therefore be necessary either to choose average farmers, or else only good farmers, and also to have some convention about the level of fertilisers to be used for the comparisons. But even this does not exhaust the troubles, for the rotation used also affects the level of yields, particularly if there are variations in the relative importance of leguminous fodder crops in the rotations compared. Hence, even this method can only be used to give a rough measure of the inherent fertility of different classes of land.

[1] L. D. Stamp, *Fertility, Productivity and Classification of Land in England and Wales*, London, 1941; *J. Min. Agric.*, 1947, **34**, 337; *The Land of Britain*, London, 1948.

Conversion Factors for Units used in the Text

Length

1 inch = 2·540 cm.
1 foot = 12 in. = 30·48 cm.
1 yard = 3 ft. = 91·44 cm.

Area

1 sq. yd. = 0·8361 sq. m.
1 acre = 4840 sq. yd. = 0·4047 hectares

Weight

1 ounce = 28·35 gm.
1 pound = 16 oz. = 453·6 gm.
1 hundredweight = 112 lb. = 50·80 kg.
1 ton (2240 lb.) = 20 cwt. = 1016 kg.

Volume

1 gallon = 4·546 litres.
1 bushel = 1·031 American bushels = 36·37 litres.
1 cubic foot = 28·32 litres.

1 lb. per acre = 1·121 kg. per ha.
1 cwt. per acre = 125·5 kg. per ha.
1 ton per acre = 2510 kg. per ha.
1 bu. per acre = 89·87 litres per ha.

1 acre foot of water = 271×10^3 gall. and weighs 1210 tons (approx.).
1 part per million (p.p.m.) of salts in water = $1{\cdot}21 \times 10^{-3}$ tons per acre ft.

To convert K into K_2O multiply by 1·20.
P into P_2O_5 multiply by 2·29.

1 bushel of wheat weighs about 60 lbs. (27 kg.).

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